1.—THE SAHUL SHELF, NORTHERN AUSTRALIA ; ITS STRUCTURE AND GEOLOGICAL RELATIONSHIPS.

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CONTENTS.

ABSTRACT.

The Sahul Shelf (*sensu stricto*) is defined as lying north of Australia between the Arafura Shelf and the Rowley Shelf. In its broader sense it includes these adjacent shelves, which are drawn closely into this study. A series of transverse " rises " (Dampier, Leveque, Londonderry, Van Diemen, Wessel, Aroe), across the shelf, separates a series of " depressions " (Rowley, Browse, Bonaparte, Arafura, Carpentaria). The rises average 10–40 and the depressions 40–70 fathoms in depth. Coral reefs occur on the rises, and near the outer edges of the depressions are perfect atolls, where the shelf edge is as low as 300 fathoms. Sedimentation is mainly calcareous debris near the reefs, while elsewhere are glauconitic and residual quartz sands and muds.

The rises on the shelf occur opposite positive Pre-Cambrian blocks on the mainland and the depressions opposite negative (paralic) basins lying between. The latter may contain 25,000 feet of Palaeozoic, Mesozoic and Tertiary shallow-water sediments. The positive blocks show only a thin veneer of sediments on the Pre-Cambrian basement. The Aroe Islands have a core of granite overlain by a thin cover of Tertiary and Quaternary, like southern New Guinea with its Mabaduan granite. No true orogenic folding occurred since middle Pre-Cambrian. Epeirogenic movements were early Caledonian, post-Permian and late Tertiary. Margins of blocks are marked by taphrogenic features : faults and flexures and " Saxonian " type folds.

Contemporary seismic disturbances along shelf margin are correlated with the buckling of the outer East Indian mobile belt. The surface of the shelf was terraced during low eustatic Pleistocene sea-levels, when small " canyons " were formed. Tectonic subsidence as well is needed to explain the closed basin on the Bonaparte Depression and the atoll-crowned marginal depressions.

I. INTRODUCTION.

The Sahul Shelf is taken here as that part of the Northern Australian continental shelf which corresponds approximately to the area occupied by the Timor Sea. Farther east the northern Australian shelf extends right across to Aroe and New Guinea, the Arafura Sea area (" Arafura Shelf "), even to the Gulf of Carpentaria. To the west it reaches to North-West Cape (" Rowley Shelf"). The writer is following Schott (1935) in regarding the whole area as part of the Indian Ocean.*

* There is a disagreement as to the boundaries of the Indian Ocean in this region. Kossinna (1921) restricted it to west of a line running through Cape Talbot (the northern tip of the Kimberley, 50 miles E. of Cape Bougainville) to the Sahul Bank and Timor. The International Hydrographic Bureau (Anon. 1928) placed all east of Cape Bougainville in the East Indian Archipelago, which belongs to the Pacific Ocean. Such divisions appear to be indefensible from both oceanographic and geographic points of view, for these arbitrary lines cross the middle of the Timor Sea and cut structural boundaries as well. Schott selected the only *natural* boundary between the Indian and Pacific Oceans, viz., Torres Straits.

Northern Australia, with its off-lying shelf and islands is one of the least known regions of the world. The available material is meagre and there are large blanks on the geological maps. There are no satisfactory topographic maps as yet, and even the nautical charts bear the following significant warning: "Caution—the whole of the coasts of North-western Australia are as yet very imperfectly examined and charted, and mariners are cautioned accordingly."

Abel Tasman was the first to prepare a rough map of this coast in 1644. William Dampier (1703) was singularly unimpressed by it, and it was only in the early nineteenth century that formal charting was begun. British naval surveyors then covered the area rather generally (King, 1827 ; Stokes, 1846 ; see historical review : Fairbridge, 1948).

A collection of rocks from these shores was described by Fitton (King, 1827 appendix), and late in the last century Hardman investigated reputed gold discoveries in the hinterland of the Kimberley and H. Y. L. Brown in the Northern Territory. The Geological Survey of Western Australia, the State geologists of South Australia's Northern Territory dependency and later various federal ventures, including the Northern Australian Geological and Geophysical Survey in the thirties of the present century, have all made useful contributions but there has been no comprehensive survey of the region.

Recent works on the stratigraphy of Western Australia are by Teichert (1947), on the Northern Territory by Voisey (1939), on the Pre-Cambrian by Clarke (1938), on the tectonic patterns by Hills (1946), on the coral reefs by Teichert and Fairbridge (1948), and Fairbridge (1950). Indispensable references are the British Admiralty "Pilot" and charts, especially numbers 1039, 1047, 1048, 2759A, and Australian Hydrographic Branch charts, numbers AUS.087, 088, 089, 094 and 097.

The present writer was attracted by the problems of this area during war-service with the R.A.A.F. Experience of the Kimberley was also obtained while engaged in an oil survey for the Caltex Co. in 1941. Aerial photos, new naval charts and other data now shed light on the general geology and structure of the region.

Acknowledgement is hereby made to the Commonwealth Universities Research Grant for financial assistance covering the typing, and to Dr. Curt Teichert for stimulating discussions. Valuable help with the drafting has been provided by the Chief Draftsman, Lands Department, Perth.

II. BATHYMETRIC MATERIAL.

(a) *Dimensions and Definitions.*

The Sahul Shelf is sometimes taken to cover the entire northern border of Australia, extending 2,000 miles from North-West Cape and Exmouth Gulf in the west to Dutch New Guinea and Torres Straits in the east, but here it is restricted to the central part, an area 500 miles long and 200 miles across. Its seaward limit is generally given as the 100 fathom contour, but should be placed at the 300 fathom line. Its northern edge comes within 75 miles of Timor, from which it is separated by a long "deep" of over 1,000 fathoms, known as the Timor Trough.

The existence of the northern Australian Shelf was first recognised as a major earth feature in 1845 by Earl, who identified both a "Great Asiatic Bank" off Malaya (the Sunda Shelf) and a "Great Australian Bank" off

Geotectonic Patterns of Northern Australia and the Sahul Shelf.

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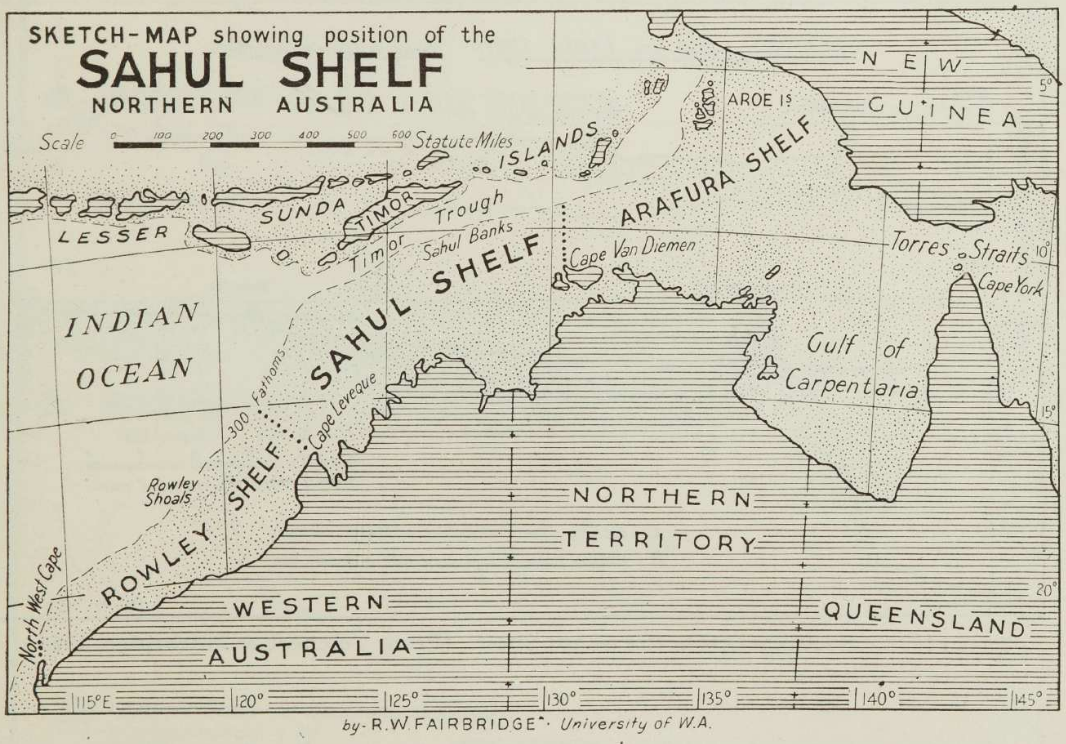
northern Australia. Krümmel (1897, vol. 1, p. 113) divided it into two, an " Arafura Shelf " of 930,000 sq. km.* (between Cape van Diemen and New Guinea), and a " North-West Australian Shelf " (covering 590,000 sq. km., between North-West Cape and Melville Island).

Without reference to Krümmel, Molengraaff introduced the terms " Sunda Shelf " and " Sahul Shelf " for the two great platforms previously recognised by Earl (Molengraaff and Weber, 1919 ; Molengraaff, 1921). " Sahul " comes from the small Sahul (Sahoel) Banks which lie on the shelf south-east of Timor and were so named four hundred years ago on Dutch charts of the area (Fairbridge, 1948).

Amongst geologists a loose application of this term " Sahul Shelf " has become rather general (Brouwer, 1920 ; Zwierzicki, 1927 ; Kuenen, 1935), but it is convenient to restrict it. Krümmel has previously named the eastern part the " Arafura Shelf," and it seems desirable to subdivide the western part into two, the natural division being an important tectonic line running north-west from Cape Leveque (from 16°20′S., 123°E. to 15°S. 121°E.), each being nearly 300,000 sq. km. The central area would be the " Sahul Shelf " (*sensu stricto*), and for the western area the term " Rowley Shelf " is proposed.



Text Fig. 1.—Sketch-map showing position of the Sahul Shelf, Northern Australia.

(b) *Edge of Continental Shelf.*

The steep continental slope in this region begins at about the 300 fathom contour, as noticed already by Kuenen (in Vening-Meinesz, 1934, p. 191). He first took it to be at 1,000 metres, but later corrected it to 500 m. (1935, p. 18).

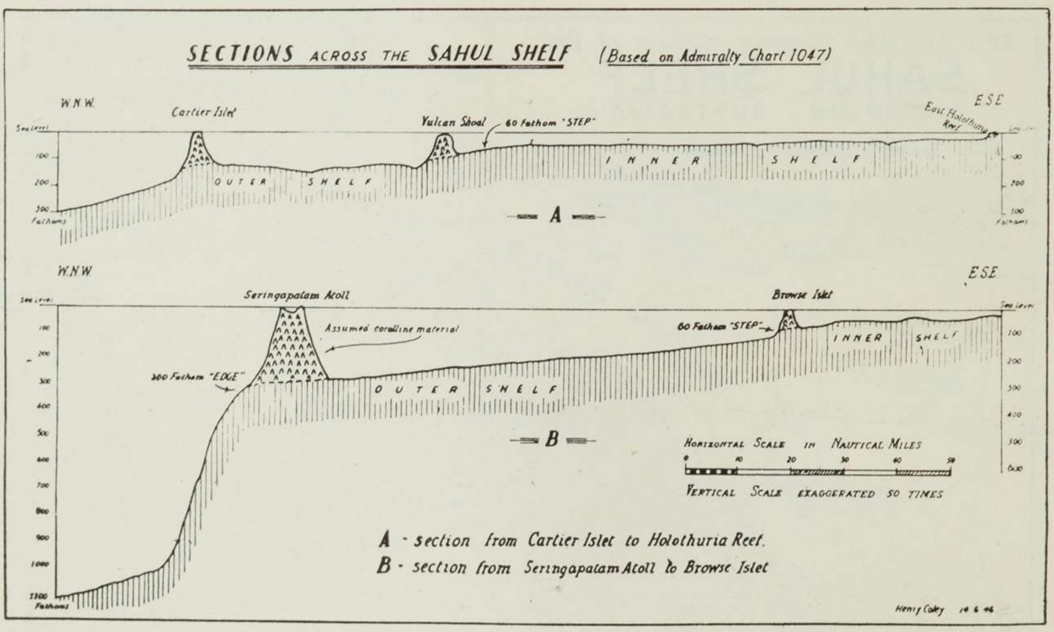
The 100 fathom (or 200 metre) contour is of no structural significance, and, as commonly marked on maps, gives the false impression of a highly convolute continental shelf margin. In places it follows broad embayments

* 1 square kilometre equals 0·386 square miles, alternatively 1 square mile equals 2⅗ square kilometres.

far onto the shelf, such as that north of Browse Island. These " bays " are only shallow depressions, however, and have nothing to do with the continental edge. In contrast, the edge of the Sunda Shelf is at about 100m. (or 55 fathoms), and Umbgrove (1929) suggested that this indicated the maximum lowering of the Pleistocene sea-level, rather than the 30–40 fathoms proposed by Daly. The lower level of the Sahul Shelf therefore requires special explanation.

(c) *Topography of the Shelf.*

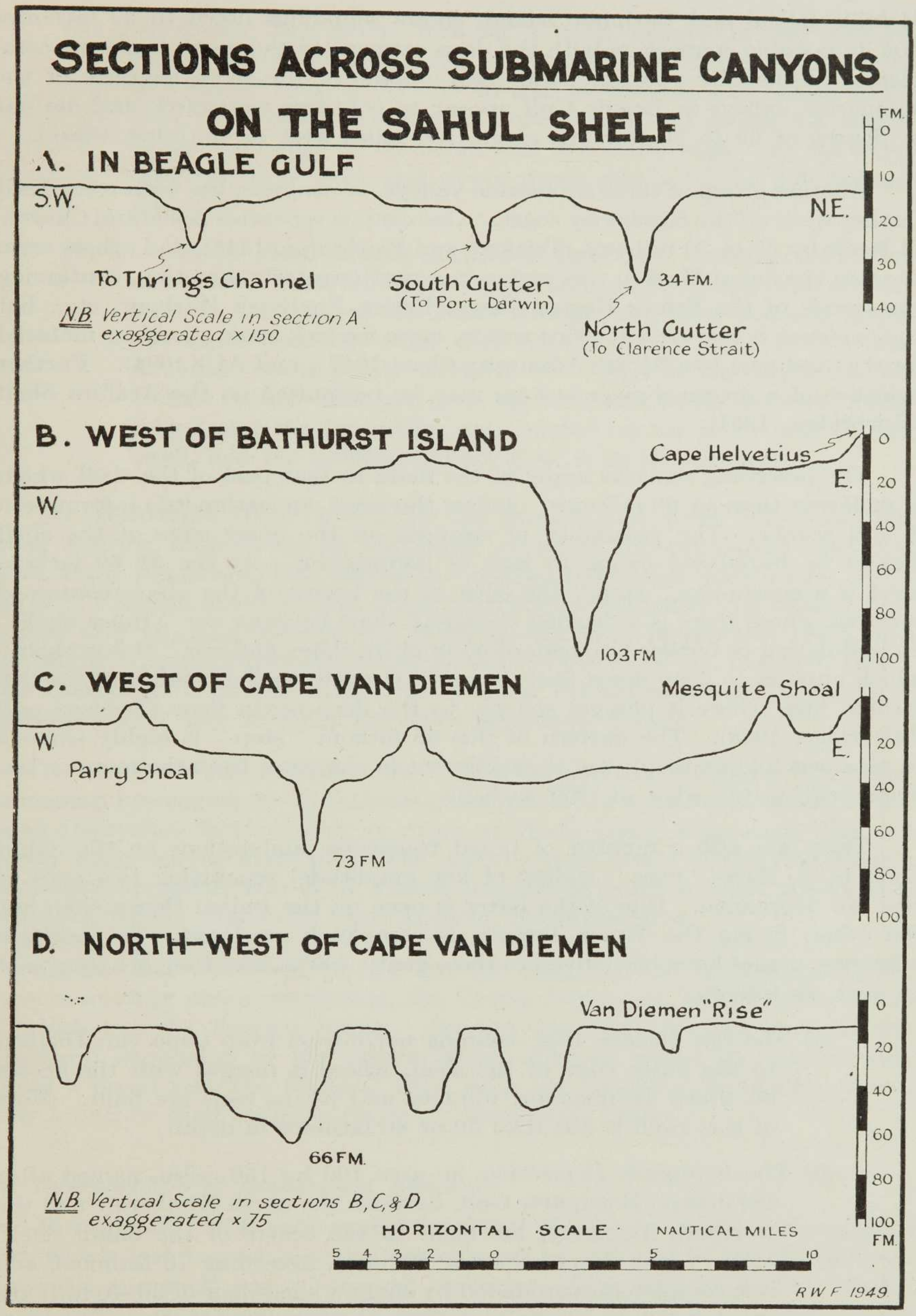
The surface of the Sahul Shelf is far from even. It lacks the smooth contours of the Sunda Shelf, where Molengraaff (1921) worked out the course of the Pleistocene river system (especially of the so-called " Molengraaff River," Dickerson, 1941). On the contrary, the Sahul Shelf is divided into many flat-topped plateaus and terraces, in places with submarine " cuestas," sloping down the shallow basins or depressions. Insufficient sounding data are available for a complete picture, but it appears that there are fairly common terrace levels at about 3–5, 10–15, 25–30, and 55–60 fathoms. The basins range from 10–70 fathoms in depth.



Text Fig. 2.—Sections across the Sahul Shelf. (From Teichert & Fairbridge, 1948.)

Cutting across these flat shelf areas are small, steep-sided canyons, apparently analogous to those found on most other shelf areas. The floors are mostly 30–70 fathoms in depth. The sides are often 100–150 feet high and are quite precipitous in places.

The most striking of these submarine valleys have been disclosed by recent sonic sounding in the approaches to Darwin (see especially charts AUS. 087, 088, 089 and 097). Here, in the area of Beagle Gulf, between Bathurst Island and the mainland, the shelf floor ranges between 10 and 17 fathoms in depth. Cutting across it, however, from south-east to north-west, are the North and South Gutters, which drop to 20 or 30 fathoms, and for long stretches are less than half mile in width. Similar deep " gutters " follow Clarence Strait.



Text Fig. 3.—Sections across submarine canyons on the Sahul Shelf.

The main submarine valley from Beagle Gulf swings around Bathurst Island to run almost due north for more than 80 miles across the shelf (where it is lost through lack of soundings). Its depth averages 50 to 60 fathoms, except in a few places where it is over 100 fathoms. As will appear below, a broad ridge extends north-west from Cape van Diemen and Bathurst Island. This rises also rather uniformly to 10 to 15 fathoms, but is intersected by channels which drop to over 50 fathoms in places. Apsley Strait, between

Melville Island and Bathurst Island, shows soundings down to 29 fathoms, but its possible connection with the deep canyons to the north is almost completely blocked by younger coral reefs. Some of the more westerly of the submarine valleys in Beagle Gulf appear to continue westwards and die out in depths of 60 to 70 fathoms about 100 miles west of Bathurst Island.

Another group of these submarine valleys, or canyons, has been recognised farther west, off the Kimberley coast. One canyon separates Adéle and Churchill Reefs by 60 to 70 fathoms (Teichert and Fairbridge, 1948), and others seem to cross the Sahul Shelf in this region in a north-westerly direction, continuing the trends of the Prince Regent River, Prince Frederick Harbour, etc., but the evidence is less clear for this region, since we lack sonic sounding material for the most part (see British Admiralty Chart 1047 ; and AUS. 094). Further evidence of a drowned river system may be recognised on the Arafura Shelf (Fairbridge, 1951).

The preceding remarks apply in the main to that part of the shelf which is shallower than 55–60 fathoms. Below this level our bathmetric information is still scanty. The possibility of canyons on the outer edge of the shelf cannot be tested yet owing to lack of information. At the 55–60 fathom level is a cuesta-like " step," the edge of the lowest of the abovementioned terraces, where there is a decided change in slope between our " Inner Shelf," an undulating or terraced plateau of no uniform slope, and our " Outer Shelf," which appears to drop down fairly steadily (1 : 400) to the vicinity of the 300 fathom line, where it plunges sharply to the deep ocean floor (Teichert and Fairbridge, 1948). The pattern of this 55 fathom " step " is highly sinuous in plan (see folding map), and thus different in character from the more or less even continental edge at 300 fathoms.

There are also a number of broad transverse undulations on the Sahul Shelf (*s.s.*), three " rises " (ridges of low amplitude) separating two axes of regional depression. One of the latter is open on the Indian Ocean side, but the other, facing the Timor Trough, is completely enclosed. To facilitate reference, names have been given to these gentle warps, and they are from east to west, as follows :

(i) The *van Diemen Rise*, running north-west from Cape van Diemen to the outer edge of the shelf, where it merges with the shoals on which Troubadour, Flinders and Evans reefs are built. Most of this swell is less than 30 or 40 fathoms in depth.

(ii) The *Bonaparte Depression*, an area 100 by 150 miles, named after the Joseph Bonaparte Gulf, between the north Kimberley and the Northern Territory, lies right in the centre of the Sahul Shelf. Most of it is deeper than 50 fathoms, exceeding 70 fathoms, and it is completely surrounded by shallow shelf-floor of 30–40 fathoms depth.*

(iii) The *Londonderry Rise*, running north-west from Cape Londonderry to the Sahul Banks, on the north-east side of which there is a connection of little more than 40 fathoms depth with the north-western end of the van Diemen Rise. The southern half of this swell is very shallow and marked by the extensive Holothuria Banks and Reefs. The northern half is practically all between 40 and 50 fathoms before reaching the shoals of the Sahul Banks.

* Shepard (1948, p. 127) has illustrated this depression.

(iv) *The Browse Depression*, forming a deep enclave in the western end of the Sahul Shelf, lies to the north of Browse Island. It is bounded roughly by the 40 and 50 fathom lines which come very close to the coast near York Sound, but swing out nearly to the shelf edge to the north-west and south-west. To the west, however, it is open and slopes down gently to the 300 fathom line.

(v) The *Leveque Rise*, running north-west from Cape Leveque, is broader and shorter than the other warps, and, unlike them, does not extend to the edge of the Timor Trough, but, after reaching about 100 miles from the coast with depths of less than 40 fathoms, it slopes down gently towards the deeps of the north-eastern Indian Ocean. The group of big reefs and banks between Adèle Island and the Lacepèdes are situated on the inner part of this swell, and the isolated Lynher Reef is on its extremity.

On the Arafura Shelf, beyond the van Diemen Rise, there follows another broad feature, marked by an eastwards sweep of the submarine contours, down to the 100 fathom line, named the *Arafura Depression* (Fairbridge, 1951). North of it comes another ridge which connects the mainland of southern New Guinea with the Aroe Islands, the *Merauke Rise* (van Bemmelen, 1949), and this finally is only separated from the foothills of the Snow Mountains of Dutch New Guinea by a narrow trough, the western extension of the Papuan Geosyncline, which may be called the *Snow Mountains Trough*.

To the east of Arnhem Land, the Gulf of Carpentaria occupies a very broad depression (averaging 30–35 fathoms), comparable in some ways to the Bonaparte Depression further west, or even, as Wade (1924) suggested, with the Desert Basin on the mainland. The north-western limits of this *Carpentaria Depression* are partly cut off by a swell of under 30 fathoms which runs north-east from Wessel Island and Cape Arnhem, the *Wessel Rise*.

In the other direction, on the Rowley Shelf, beyond the Leveque Rise, there is another major depression, the *Rowley Depression*, in the outer centre of which rise the Rowley Atolls. On the coast side lies Broome and the structural depression of the Desert Basin. Closing round its western side comes a broad rise, the *Dampier Rise*, from the Dampier Archipelago there. Only a narrow shelf connects finally to North-west Cape.

(d) *Interpretation of Bathymetric evidence* :

Molengraaff (1921) interpreted the Sahul Shelf as a continental marginal area which had been completely peneplaned by the end of the Pleistocene. However, the shelf has a terraced character. The terraces at 3–5, 10–15, 25–30 and 55–60 fathoms may be simply explained by erosion during eustatic lowerings of sea-level during the Pleistocene, as noted already in the Abrolhos and Peron regions of Western Australia (Fairbridge, 1950b), and by others in many parts of the world (Daly, 1934 ; Zeuner, 1945).

Evidence of the mid-Recent eustatic emergence of 10 feet is also widespread along the shores of the Kimberley and Northern Territory (Cadell, 1899 ; Brown, 1906 ; Woolnough, 1912 ; Jensen, 1914 ; Basedow, 1916, 1917), as well as on the major off-lying islands (Teichert & Fairbridge, 1948), and on adjacent East Indian islands (Kuenen, 1933 ; Umbgrove, 1947b). These indications of uniform submergences and emergences lead to the conclusion that the inner part of the shelf and mainland shores have been fairly stable geologically, at least during the latter part of the Quaternary. On the other hand, evidence from Timor suggested great instability continuing right up till Recent times (Molengraaff, 1913).

The inner part of the shelf appears as a drowned landscape, which may well have been developed during arid cycles of erosion. It was a plateau, terrace and plain country in which the streams were fairly deeply incised, the down-cutting having been revived in stages to present a step-like cross-section to the canyons. The surface, in short, is just like that of many parts of the adjacent Kimberley and Northern Territory today.

In certain areas, however, such as in the submerged ridge north-west of Cape Van Diemen, the streams appear to have cut down canyons of antecedent character, since they are deeper in the centre of the ridge than either north or south of it. Parts of these shelf canyons, being over 100 fathoms in depth, cannot be explained by the normal eustatic processes. Some Quaternary tectonic movement may have occurred here.

The terraced (inner) section of the shelf comes to an end at the 55–60 fathom " step ", which thus seems to be a feature of rather special significance. This level is often regarded as the extreme limit of eustatic lowering of sea-level during the Pleistocene. The steady outward slope from the "step" down to the continental edge suggests another explanation for the outer shelf, perhaps tectonic subsidence. It is significant that isolated coral reefs rise respectively from near the edge of the 55–60 fathom " step " and near the outer (300 fathom) edge. For discussion of this problem see Section VI.

The difference between the Sahul Shelf and the Sunda Shelf is possibly due in part to climatic factors. Large tropical rivers like the Solo, Barito and Moesi are continuously adding vast quantities of sediment to the Sunda Shelf, while the hinterland of the Sahul Shelf is semi-arid, and the rivers are consequently seasonal and small compared with those of Java, Borneo, and Sumatra. The tremendous volume of these Sunda Shelf sediments has been stressed by Tercier (1939) ; for example the Solo River of Java carries approximately eight times the sediment of the Rhine. The nature and provenance of the Sunda sediments has recently been described by van Baren and Kiel (1950).

It is suggested, therefore, that excessive sedimentation is quickly obscuring signs of Pleistocene terracing and stream revival in the Sunda Shelf, while relatively slow sedimentation on the Sahul Shelf leaves the angular topography still relatively bare. It is possible that greater exposure to powerful tides and currents on the Sahul Shelf is a contributing factor in keeping it clear, as in the case of Adèle Reef (Teichert and Fairbridge, 1948).

The concept of the Sahul Shelf as dry land at times during the Pleistocene is far from new. From the zoogeographic point of view Wallace (1869) found evidence of Pleistocene migration across the Torres Straits (where an emergence of less than 10 fathoms would provide a bridge from New Guinea to Australia), but while there was a ready interchange of the more mobile creatures across the Timor Trough (1,000 fathoms deep), there was always maintained some sort of sea barrier here, even though it must at times have been very narrow.

Without apparently giving much thought to the geological implications of the hypothesis, Rensch (1936) postulated a Pleistocene land-bridge across the Timor Trough to account for the zoogeographical relationships. Mayr

(1944a), after exhaustive investigations, came to the conclusion that Wallace was right, and that despite the well-recognised Glacial lowering of sea-level, the depth of the Timor Trough would long have maintained a certain barrier, which permitted the passage of only specialised classes of migrants. For earlier times he follows Kuenen (1935, p.107) in believing that there were continental connections between Australia and the East Indies up till the early Eocene, but that the zoogeographic evidence demonstrates a complete separation between these two from Eocene till the early Pleistocene.

Mayr's special study, the avifauna of the East Indies and adjacent areas, also provided the interesting conclusion that since most of the recent arrivals in Australia from Timor were grassland birds, there must have been arid, savannah-type of country on the Sahul Shelf during the periods of migration (Mayr, 1944b.)

Support for this idea is the climatological conclusion of C. F. Brooks (in a personal communication, cited by Mayr, 1944b), who observed: "By closing Torres Straits and making most of the Sahul Shelf dry land, the climate in the southern hemisphere winter would be very dry, and opportunities for rainfall in the southern hemisphere summer would be reduced. The North-West monsoon would be drier than it is today, after passing over the higher mountains and more continuous land of Pleistocene times. I should think that the summer climate in the thus protected area west of New Guinea and north-west Australia might well have been arid........" Quite recently Gentilli (1949) has prepared a series of palaeoclimatic maps of Australia for the Pleistocene, which clearly illustrate this widespread desiccation at certain stages.

It is apparent also that for long periods during the Pleistocene, the great transverse "rises" recognised in the regional bathymetry of the Sahul Shelf would have been emergent promontories, thus extending the periods during which migration would be favoured beyond the brief limits of the extremely low sea-levels.

Most of the depressions on the other hand, with their broad shallow bays at such times, would seem to favour the development of extensive mangrove swamps, while the Bonaparte Depression may have been reduced to a swampy lake whenever the sea-level was more than 30-40 fathoms below the present.

III. CORAL REEFS AND SEDIMENTS OF THE SHELF.

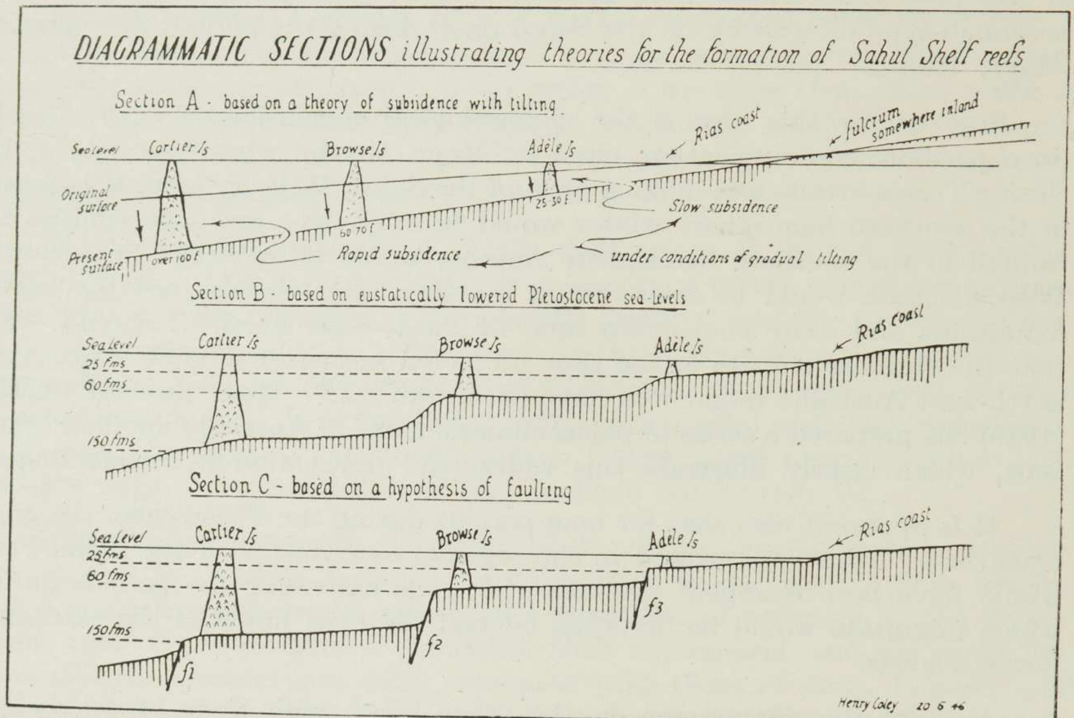
Both coral reef accumulations and normal sedimentation contribute towards the covering of superficial material on the surface of the shelf.

(a) *Coral Reefs and other islands.*

The distribution and significance of the coral reefs have been discussed by Teichert and Fairbridge (1948), and further in their regional setting (Fairbridge, 1950b).

There is firstly a disconnected row of reef platforms and atolls arising from fairly deep water (down to nearly 300 fathoms) along the outer edge of the shelf (including Scott, Seringapatam, Ashmore, Sahul Bank, Troubadour, etc.), which in places forms an ill-defined barrier. Scattered intermediate reefs rising from levels between 40 and 60 fathoms (including Cartier, Browse, etc.), and in shallow water near the coast are the large platform and fringing reefs (including Lacepèdes, Adèle, Holothuria, etc.).

Those reefs nearest the coast are controlled by the contours of the basement (Pre-Cambrian). In some that basement is showing and in others it is even predominant, so that the coral is reduced to the status of a discontinuous fringe. The intermediate row of reefs grow up from near the 55 fathom " step," which may mark the limit of the lowest Pleistocene sea-level. The outermost row, however, rising as it does from deep water, well below the growth range of normal, living corals, suggests that slow subsidence has been taking place here, either by step-faulting or by a slow tilting towards the exterior. There is no sign of any drowned volcanic stocks (such as Hesse's " Guyots," or sea mounts), or other basement elevations, which makes the occurrence of perfect atolls here particularly interesting.



Text Fig 4.—Diagrammatic sections illustrating theories for the formation of the Sahul Shelf reefs. (From Teichert & Fairbridge, 1948.)

The " continental " islands, which are also mainly surrounded by fringing coral, occur chiefly in the Buccaneer Archipelago, off the north Kimberley coast, and are composed of Pre-Cambrian rocks. The large islands off the Northern Territory, including Bathurst and Melville Islands, are mainly Tertiary and Cretaceous on a Pre-Cambrian basement (*see* also Section V.). With the sole exception of the Aroes, however, there are no continental islands at any great distance from the shores of the mainland.

(b) *The Sediments.*

The size of the Sahul Shelf, and its geographical relationships, should make it a particularly interesting area for the study of sediments. The rivers from the semi-arid interior and sub-tropical margins of the continent are strictly seasonal in character. We may expect, therefore, the outer parts of the shelf, 100 to 200 miles from land, to have a very slow rate of terrigenous sedimentation, but sediments from other sources should be relatively important.

One of the earliest references to the sediments of the shelf comes from Captain Heywood, R.N., who, in 1801, referring to the area roughly between the Sahul Banks and the Holothuria Banks, described the irregular way in which coral shoals rose up steeply from the general level of the shelf, " close to them the bottom was generally coarse sand and bits of shells ; farther off, fine sand ; and when clear altogether, a sort of green sandy ooze " (*see* Horsburgh, 1811). Stokes (1846, vol. II, p. 119) in the same area found in the shallows " coral with bits of ironstone mixed with sand ; whilst in the greater depth, it was green sandy mud." The " ironstone " referred to sounds very much like laterite, which is such a characteristic feature of subaerial weathering on the continent.

From the general evidence of Admiralty soundings these descriptions are widely applicable. Many subsequent naval surveyors have referred to the sediments, in greater detail, but in the same general terms. Coral sand and debris is marked at many points on the charts in depths from sea-level down to 100 fathoms. Actual living coral is reported from quite considerable depths ; in Sunday Strait, Stokes (1846, vol. I, p. 185) noted a particularly beautiful fragment from 30 fathoms. Farther out there are clearly many submerged reef patches which do not come yet within many fathoms of the surface. Nevertheless, by far the greatest area is floored with " mud " of one sort or another.

No systematic sampling has been carried out on the body of the Sahul Shelf, but on the Arafura Shelf we have the advantage of a series of dredgings made by the " *Challenger* " Expedition (1872–76), between the Torres Straits and Aroe (stations 186 to 190, *see* Murray and Renard, 1891, chart 31). The data show that near the coral islands in the Torres Straits, the sediments are mainly coral sands with foraminifera. Three soundings right out on the shelf (188–190) show " green, sandy mud " or " green mud." It is perhaps worth summarising the material on these three stations, as indicating a typical cross-section of the shelf deposits (where they are well clear of the coral reefs) :—

Station 188 in 28 fathoms	(9°59′S., 139°42′E.) Green, shelly sandy mud : 38% $CaCO_3$ (15% foraminifera and 23% other shells) ; 3% siliceous organisms ; 45% quartz, glauconite, felspar, hornblende, etc. ; 13% " fine washings."
Station 189 in 28 fathoms	(9°36′S., 137°50′E.) Green mud : 31% $CaCO_3$ (10% foraminifera, 21% other shells) ; 3% siliceous organisms ; 25% quartz, glauconite, mica, tourmaline, zircon ; 40% " fine washings."
Station 190 in 49 fathoms	(8°56′S., 136°05′E.) Green mud : 23% $CaCO_3$ (4% foraminifera, 19% other shells) ; 2% siliceous organisms ; 50% quartz, glauconite, felspar ; 25% " fine washings."

Of these analyses the " fine washings," as explained by Murray and Renard (1891, p. 24–5), refer mainly to insoluble material of fine nature, which was largely made up of minute clay and heavy mineral grains. Some of this material may well be wind-borne to the Sahul Shelf, since the south-east winds from the continent of Australia are a very persistent feature. As many authorities have shown, such as off the west coast of Africa, aeolian constituents may go to make up a considerable fraction of the whole sediment.

The high calcium carbonate percentages are, of course, to be expected and the green coloration is mainly due to the glauconite. The latter is a highly significant mineral in sedimentation : it suggests a shelf deposit of terrigenous origin—being common off desert and semi-arid shores, where other terrigenous deposits do not mask its development ; in stratigraphy it is taken to indicate very slow accumulation and even disconformities (Hadding, 1932).*

The careful surveys of the *Snellius* Expedition in the East Indies were carried right across the Timor Trough up to the edge of the Sahul and Arafura Shelves in many places, and the results of the bottom sample analyses have appeared recently (Kuenen and Neeb, 1943). At several places right on the edge of the shelf are coral muds ranging from 95 to 99 per cent. $CaCO_3$. The coarse fractions, strictly coral *sands*, are relatively important in the vicinity of the Sahul Banks proper, but since none of these reefs are awash today, the sediments must date back to before the recent " drowning " by subsidence, or even to the Pleistocene period when they were exposed periodically to wave action.

As regards the deep-water sediments, off the edge of the Sahul Shelf, towards the Timor Trough and the Wharton Deep (North Australia Basin), the Admiralty charts show extensive developments of globigerina ooze, and blue terrigenous mud in the direction of Timor. Pteropod ooze is noted off the southern tip of Tanimbar and radiolarian ooze is recorded below 1,000 fathoms in the middle of the Timor Trough south of Sermata. Right out in the Wharton Deep, below 3,000 fathoms, one finds the usual red mud.

While the globigerina ooze belt ranges from the edge of the shelf down to about 1,000 fathoms in the centre of the trough, from there on to the shores of Timor is all a belt of terrigenous mud, which clearly came from the north (Kuenen and Neeb, 1943). Of particular interest is the recognition of two special belts of terrigenous origin, superimposed on the globigerina ooze belt, which appear in contrast to come from the south and east, i.e., the shelf region. These respectively run from near Troubadour Reef to south of Tanimbar and from there right round the Aroe Basin to beyond the Bomberai in Dutch New Guinea. The first is marked by the appearance of minerals of igneous and metamorphic origin, notably epidote, and the second by quartz grains apparently derived from some dominantly sandy formation. The old igneous province to the south appears to be the extension of Archaeozoic rocks in the van Diemen Rise, and the sandy province in the east probably the Proterozoic-Mesozoic sandstones extending from Arnhem Land on the Arafura Shelf. Their distribution can best be explained as deltaic deposits of the Pleistocene streams described above.

The deepwater sediments of the East Indies (*see* Kuenen, 1939 ; Kuenen and Neeb, 1943 ; and Tercier, 1939) are completely different from those of the Australian area. Furthermore they are types which do not seem to occur at any time throughout the sedimentary evolution of northern Australia. The conclusion, therefore, would be that the Sahul-North Australian region has always been of shelf, shallow basin, or continental nature since the Pre-Cambrian. That this shelf has varied periodically from the true continental (emergent) to the epicontinental (with low shores and reduced sedimentation),

* The source of the glauconite has been traced to many substances, foraminiferal tests (Murray and Renard, 1891, pp. 378–391), coprolites and a variety of minerals. Galliher (1936) demonstrated a continuous gradation from biotite to glauconite, from biotite sands near the shore to pure glauconite mud near the 100 fathom line. Glauconite however forms also where there are no great quantities of micas (Hendriks and Ross, 1941, and others). Takahashi (1939, p. 503), concluded that glauconite was only formed under marine conditions where the summer water temperature was not less than 15°C. with normal salinity ; the process was one of submarine metamorphism under anaerobic or reducing conditions, generally associated with iron sulphides. Subsequent reworking may lead to concentration with other heavy mineral sands. The glauconite may originate from a variety of original minerals : felspar, mica, pyroxene, or from similar clayey material filling the tests of organisms such as foraminifera and radiolaria or replacing faecal pellets. The presence of organic matter thus favours the process, which involves the hydration of silica followed by the absorption of bases and the loss of alumina.

to the paralic (with higher relief and increased sedimentation), should appear from the geological discussions to follow. In these characteristics it has something in common with the Sunda Shelf, though the borders of the latter appear to be structurally much more active.

Tercier (1939) has emphasised that the difference between the Sunda and Sahul Shelves is more one of climate than of depth. The Sunda Shelf, on the one hand, is entirely within the equatorial belt and as noted above there is fine sedimentation on a tremendous scale. Against this, the sediment brought down by north Australian rivers to the Sahul Shelf is almost negligible. Only in the north-east are comparable conditions found, where the rivers from the Snow Mountains of Dutch New Guinea bring down plentiful sediment to the northern side of the Arafura Shelf. The very fine reddish white clays of southern Dutch New Guinea, which are found as far south as Merauke (Heldring, 1910) and even in Aroe, appear to be from this source (Sperling, 1936). The relative absence of alluvial plains in northern Australia is in striking contrast to the broad tracts of southern New Guinea and the coastal lands of Java, Sumatra and Borneo which face the Sunda Shelf. In contrast to the Sahul Shelf, there is extremely little glauconite anywhere in East Indian sediments (Molengraaff, 1929, p. 991).

Fine terrigenous sedimentation on the Sunda Shelf thus contrasts with coarser material on the Sahul Shelf. The conditions favour coral reef growth on the latter, and also inhibit it on the former except in places kept clear by currents (Umbgrove, 1947b). Fringing reefs are almost unknown along the mainland shores of the Sunda Shelf, but are common along the north Australian coasts, except in those places where loose sands, river mouths and mangrove present unfavourable habitats.

Quaternary events in the region do not disclose any indication of sedimentation on the Sahul Shelf having been much faster, except during the short stages of rising sea-level associated with deglaciation. Slow sedimentation seems to have been the rule for long periods in the past. In places there may be only a thin veneer of sediments resting on a Pre-Cambrian basement.

Tercier takes the Sahul Shelf (along with Yucatan, Florida and Bahama Shelves) as the type area of his " neritic sedimentation of epicontinental platforms," which are characterised by limestone, marls and calcareous shales, with very reduced amounts of terrigenous material. Against this he classifies the Sunda Shelf (along with the northern coast of the Gulf of Mexico) as " neritic sedimentation of paralic platforms," characterised by very thick terrigenous deposits, alternating between marine, estuarine and continental facies, including coal measures.

One factor, however, seems to have been rather neglected by Tercier : that of the siliceous and heavy materials on the epicontinental platforms. These components are insoluble and fairly coarse grained. They are common and often predominant in northern Australian sediments. In areas of strong currents they are left behind when fine material is swept away ; on land they are concentrated by the leaching out of soluble fractions and by wind. In this way they would appear to be of great longevity, being reworked and redeposited again and again through geological time. With a shallow shelf and a low continental shore, eustatic oscillation of the sea-level seems to be the most important factor in this cycle.

IV. GEOLOGY OF THE ADJACENT MAINLAND.

Nothing is known directly of the geology of the Sahul Shelf, since no continental rocks are exposed on it. So we must look for analogies on the adjacent mainland. Structurally the northern parts of Australia consist of a number of major tectonic blocks, which are marginal to the great Pre-Cambrian Shield, and show alternating positive and negative tendencies to rise or sink during post-Archaean times. Only the early Pre-Cambrian rocks of this region are extensively folded, metamorphosed, and intruded by granites.

All subsequent sediments are flat-lying or gently folded, and hardly at all metamorphosed. The folding is restricted to narrow, active belts associated with the margins of the blocks, which are generally bounded by major normal faults, monoclines or broad warps. Post-Archaean diastrophism is thus mainly epeirogenic, with restricted taphrogeny (fragmentation) and fault-folding of Saxonian type. In the basins sediments are up to 20,000 feet or so, while on the rising blocks Wade (1924) has allowed not more than 500 feet for the entire sedimentary succession ; they are, he says, parts of "the oldest and most persistent land areas in the world."

It seems desirable to identify the individual structural units of the mainland, and, from west to east, they are :—

(a) Pilbara Block.
(b) Desert (Canning) Basin.
(c) North Kimberley Block.
(d) East Kimberley Basins.
(e) Western (Daly-Victoria) Rivers Basin.
(f) Arnhem Land Block.

Owing to serious gaps in our geological knowledge of these areas, boundaries are only poorly defined, and there is room for much further study.

(a) *Pilbara Block.*

Of mainly Pre-Cambrian rocks, it forms the northern end of the Great West Australian Plateau, and its southern boundaries are thus somewhat arbitrary (Jutson, 1934). It consists of a high but deeply dissected plateau, dropping to a narrow coastal plain and to the low Desert Basin (q.v.) in the north-east.

The basement of ancient Pre-Cambrian metamorphic rocks is mainly covered by flat-lying or undulating Nullagine sediments, generally considered to be late Proterozoic. Trends in the older rocks on the north-west (coastal) side are N.E.-S.W., while to the south-west and north-east they are N.W.-S.E. (Hills, 1946). These older trends are also reflected in the gentle folds and block-fault patterns of the Nullagine physiography. The Nullagine structures appear to be early Caledonian, but were modified by warping and faulting in post-Permian and even late Tertiary times.

(b) *Desert (Canning) Basin.*

A roughly rectangular unit, bounded by the Eighty-Mile Beach on the north-west, and covering some 140,000 square miles, the Desert (or Canning) Basin is filled mainly with Permian and older Palaeozoic sediments (Teichert, 1947, 1950 ; Guppy and Opik, 1950 ; Reeves, 1951), which appear to have accumulated to a thickness of over 20,000 feet in a deep trough coinciding with the Fitzroy Valley and lying on the south-east of the North Kimberley

Block. Post-Permian marine sediments are known along the coast, where Jurassic sandstones are found in bores (Teichert, 1939, 1940, 1947). Other sandstones near the coast are Cretaceous (Brunnschweiler, 1951) and there may be a little Tertiary, but diagnostic fossils have not been found. The beds of the Desert Basin are folded and upturned along the north-eastern margin, thus showing N.W.-S.E. strikes, associated with the secondary folding and faulting (Wade, 1924, 1936). The initial subsidence of the basin was in early Palaeozoic times, culminating at the end of the Permian and later periodically revived, movements which were probably paralleled by regional upwarps of the adjacent Pre-Cambrian massifs.

(c) *North Kimberley Block.*

This is another rectangular-shaped block, but forming a plateau of about 90,000 square miles, the sides trending N.W. and N.E. It is capped by gently undulating sediments, mainly sandstones, intercalated by basalts and generally taken to be Nullagine in age (Clarke, 1938). The basalts are of "plateau" type (Edwards, 1942). The youngest of the basalts is regarded as of Lower Cambrian age (Teichert, 1947).

Older, highly folded, rocks of Mosquito Creek and Warrawoona age underlie the Nullagine rocks at no great depth and outcrop along the margins of the block in the Leopold Range and extend north-west to the Yampi Sound area, where the regional strike varies from W.N.W.-E.S.E. to N.W.-S.E. The same trends may be followed out on the continental shelf beyond Cape Leveque (Wade, 1936 ; Teichert and Fairbridge, 1948), in what we are now calling the "Leveque Rise."

The overlying Nullagine rocks are subject to a regional jointing in N.W.-S.E. and N.E.-S.W. lines, as shown by the stream patterns and by margins of the block. Epeirogenic upwarping has continued since before Nullagine times, movement occurring especially in late Cambrian and post-Permian tmes and extending even to late Tertiary times (Hills, 1946). Jutson (1934) describes the North Kimberley as an old peneplain in the course of vigorous youthful dissection by a great number of streams (there is a mean rainfall of 20–60 inches). The coast is very precipitous and it was compared already by Gregory (1913, p. 347) with ria coasts. Most fiord-like is the Prince Regent River, which is 240 feet deep not far from its mouth, but then the floor rises again to a threshold ; such a feature, Gregory contended, prevents it being called a true ria coast, but this may well represent a subsequent, sedimentary accumulation of no genetic significance.

There is a fundamental difference between the north-west and north-east coasts of this block. The former is a ria coast with numerous off-lying islands and reefs which grow up presumably from submerged continental ridges, including the Leveque and Londonderry Rises. The north-east coast has an almost rectilinear trend (N.W.-S.E.), no rias, no offshore islands, no reefs, and drops off steeply into quite deep water. It thus appears to be faulted, and the line may be called the "Cambridge Fault" after Cambridge Gulf, which is cut off by it. The same fault appears to continue to the south-east from the mouth of Cambridge Gulf, separating the North Kimberley Pre-Cambrian rocks from the Permian of the Bonaparte Gulf region (Dr. Frank Reeves : personal communication).

(d) *The East Kimberley Basins.*

Abutting against the eastern margins of the North Kimberley Block is a complex shatter zone of severely faulted basins and horsts. Maitland (1919) depicted only a single " Gulf Basin " here, but Matheson and Teichert (1948) distinguished several more. Reeves (1951) called the main one the " Bonaparte Gulf Basin."* These basins contain probably 5,000 feet of Nullagine and Cambrian sediments with basalts (see Edwards and Clarke, 1940), and are followed uncomformably by 12,000 feet of Devonian, Carboniferous and Permian.

The structural history appears to be somewhat similar to that of the Desert Basin but is more complex. The movements were probably most active in the late Cambrian, post-Permian and later Tertiary to Recent times. Even late Tertiary lake deposits have been deformed (Matheson and Teichert, 1948), which provides an explanation for the youthful physiography of this belt. Its youthful subsidences appear to be connected with the downwarping of the Bonaparte Depression lying to the north.

(e) *Western (Daly-Victoria) Rivers Basin.*

This is an imperfectly defined region of about 80,000 square miles which occupies the north-western part of the Northern Territory of Australia.† Structurally, it is a broad shallow basin, which may be related to the East Kimberley Basins in the same way as the centre of the Desert Basin is to the complex north-eastern belt of Permian and Devonian in the Fitzroy belt. It is underlain by older Pre-Cambrian (Mosquito Creek) metamorphic rocks granites which emerge to form its eastern boundary, outcropping in the east along the Darwin-Katherine watershed, and also appearing in a belt parallel to the coast 20–30 miles inland. The " grain " is essentially N.W.-S.E. to N.N.W.-S.S.E.

The centre of the basin is occupied by gently undulating areas of Cambrian and Nullagine (Woolnough, 1912). On these are isolated buttes and small plateaus of flat-lying Mesozoic beds known as " Pleateau Sandstones." They are generally not more than 50 to 100 feet in thickness. At Buldiva they were found to contain *Otozamites* and so regarded as Jurassic. From foramnifera Miss I. Crespin (pers. communication) believes that they are Lower Cretaceous.‡

On the seaward side of this basin, beyond its north-west border of early Pre-Cambrian, there is a 2,000 square mile belt of Permian and possibly Carboniferous (Brown, 1895 ; Woolnough, 1912 ; Basedow, 1916). They are generally flat-lying, but locally have gentle dips and strike E.-W. or N.E.-S.W. Farther north-east from Anson Bay to Darwin the coastal stretch is occupied by an area of marine Cretaceous rocks (Brown, 1895, 1906). Recent work by Noakes (1949) indicates that these overlie continental sandstones inland.

* Now described in more detail by L. C. Noakes, A. A. Opik and Irene Crespin : " Bonaparte Gulf Basin, North Western Australia. A stratigraphic summary with special reference to the Gondwana System." Congr. Geol. Internat. (XIX., Alger, 1952).

† The name " Western Rivers District " was used by Basedow (1916) ; it is not a political or historic unit, but covers the Daly-Victoria basins quite appropriately).

‡ They have named " Mullaman Group " by Noakes (1949) ; *see* also Noakes, Opik and Crespin : " Bonaparte Gulf Basin . . . ." (*vide supra*).

(f) *Arnhem Land Block.*

Covering more than 70,000 square miles, this block is bounded by the Darwin-Pine Creek-Katherine line, the Roper River, the Gulf of Carpentaria and the Arafura Sea. It is a great dissected dome, consisting of an ancient peneplaned block, overlain by a thin veneer of late Proterozoic (Nullagine) and Mesozoic sediments (Jurassic, of Voisey, 1939) which was regionally up-warped in Tertiary times. While the bedding is only gently undulating, in the north-coastal parts there is marginal block-faulting, with monoclinal folds and steep dips (Brown, 1908 ; Jensen, 1914). Faulted blocks trending N.E. and dipping 2–5° N.W. condition the orientation of Wessel Island and vicinity, and Jensen mentions a secondary set of faults here, trending N.W.–S.E. The highest parts are probably fault-bounded horsts (Jensen and Playford, 1913). Out on the continental shelf the north-west trend of the Pine Creek line appears to be extended in the van Diemen Rise.

Lying beyond the Arnhem Land Block to the east comes the broad depression of Carpentaria. This may be an old Pre-Cambrian block (Jensen's "Carpentaria Massif," 1923 ; Hills' "Carpentaria Nucleus," 1946), but it was repeatedly flooded by epeiric seas during the late Palaeozoic, Cretaceous and Tertiary times. Heldring (1910) believes the entire region from southern New Guinea to the Gulf of Carpentaria, west of his "Torres Strait Horst" and east of the Aroes, forms an immense elliptical "senkungsfeld" today. Thus it has now begun to assume the role of a shallow basin—an interesting reversal in character.

(g) *Aroe Islands.*

Situated 400 miles out on the Arafura Shelf north of Arnhem Land, the Aroes represent the only continental shelf islands so far out. Wichmann (1887) regarded them as an outermost East Indian arc, a view supported by Koto, but subsequently all authors have agreed that they belong structurally to the continent (Gregory, 1924 ; Fairbridge, 1951).

The islands consist of a Miocene-Pliocene limestone plateau, much jointed and dismembered into blocks and recemented by a cover of young coral limestone (Verbeek, 1908, p. 475 ; Gregory, 1924 ; Zwierzicki, 1927, p. 312 ; Kuenen, 1933). The Mio-Pliocene beds are very gently undulating (Tayama, 1936). Coarse grains of terrigenous minerals in the sediments indicate that the basement is not far off and at Kampoeng Sia (Serani), Tissot van Patot (1908) reported granite*, which may be compared with a similar boss of granite at Mabaduan on the south coast of New Guinea (Gibb Maitland, 1892 ; David, 1932, fig. 8), where the shallow basement is recognised from oil-well drilling.

The age of these two granites has not been determined, but since there appears to be no significant tectonic boundary separating them from the early Pre-Cambrian crystalline rocks of the Northern Territory and North Queensland, it seems safer to accept their Pre-Cambrian age (Fairbridge, 1950c) than to assume completely hypothetical Caledonian and Hercynian orogenic belts across this area as done by Kölbel (1945), Stille (1945) and Glaessner (1950).

Regarding the Quaternary history of Aroe, there are several significant features. First, there is the essentially "Australian" character of the Aroe fauna and flora. Earl (1845) believed that the presence of the kangaroo on

* Recently Van Bemmelen (1949) quoted a personal communication from A. Heim to the effect that only coarse sands were found at this spot.

Aroe showed an original connection with Australia and New Guinea. Further zoogeographic evidence leading to the same conclusion was gathered by many authorities (*see* Wallace, 1857 ; Longman, 1924 ; Sperling, 1936 ; Keble, 1947). Such land connections would automatically have come about during low Pleistocene sea-levels.

Secondly, there are no emerged Pleistocene coral-reefs on Aroe (Kuenen, 1933). If stable conditions had existed, one would expect to find such reefs at the appropriate heights corresponding to the various high eustatic sea-levels of the Pleistocene. It would seem that the islands had not yet been elevated.

Thirdly, there are the peculiar " soengeis " (Malay : river), which are deep channels crossing the islands from side to side (*see* text fig. 5). Wallace (1857, p. 479) suggested that they were remnants of drowned stream beds, from rivers that formerly flowed across the shelf from the Snow Mountains of New Guinea. From the angular pattern of the soengeis, van Hoëvell (1889), Verbeek (1908), Merton (1910), Brouwer (1917), van Straelen (1933), and others have concluded that the initial lines of weakness were due to jointing or even faulting. Study by the writer of recent air photographs confirms the joint patterns but no fault displacements were observed. Similar jointed structures are crossed by antecedent streams (Merauke and Digoel) in southern New Guinea (Heldring, 1910), and there seems little doubt that Wallace was essentially right in the case of the Aroe soengeis. It is doubtful, however, if these antecedent streams would have come from so far as the Snow Mountains, for the soengeis are hardly wide enough to represent big valleys.

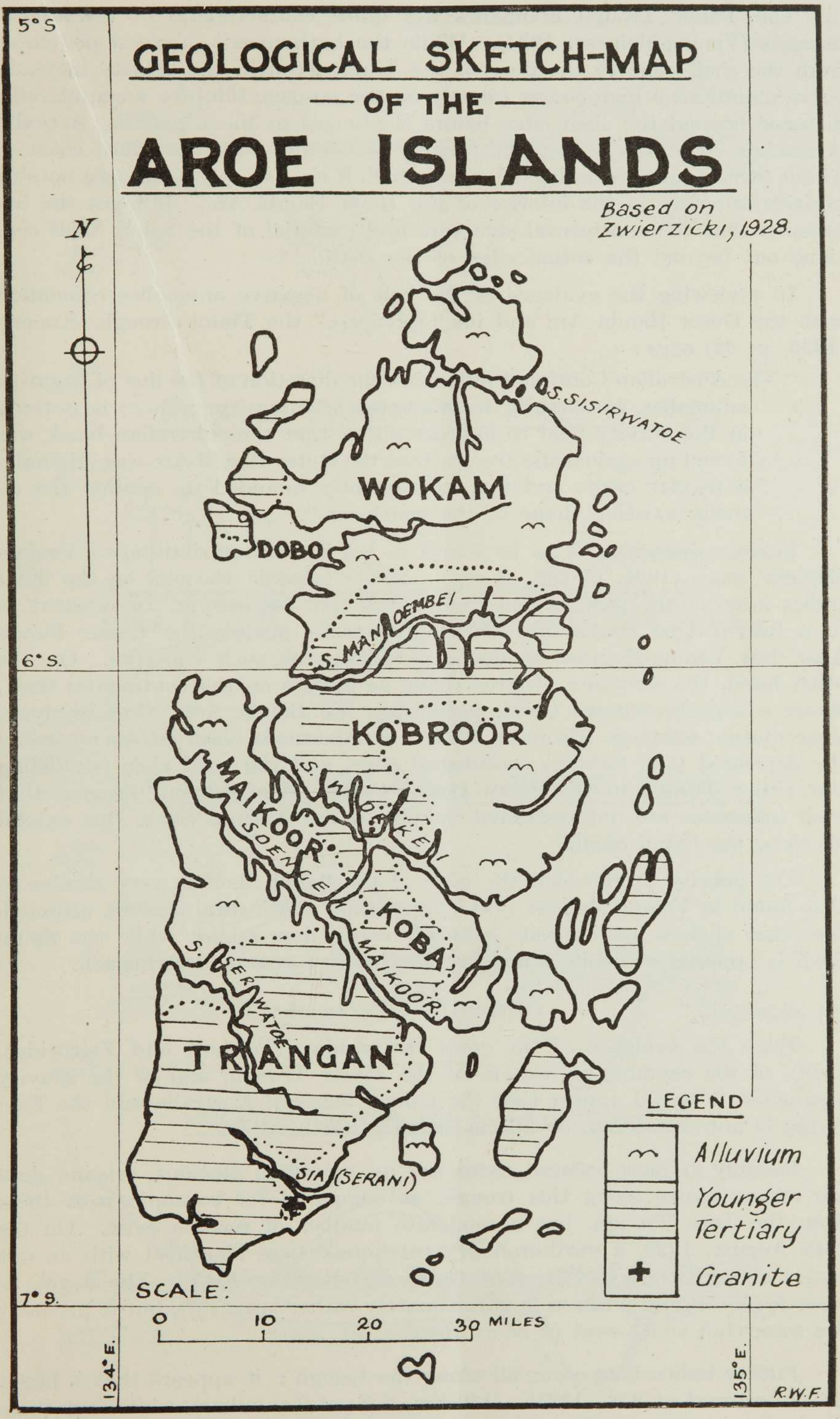
From this Quaternary material one may conclude that the Aroe Islands represent the summit of a broad ridge (an extension of the Oriomo axis of southern New Guinea, Carey, 1938), which was slowly arched up from the Arafura Shelf towards the close of the Pleistocene, thus producing rapid down-cutting of stream-beds which were maintained during the upwarp. The islands were well elevated by mid-Recent " Atlantic " times, so that they formed a refuge for Late Pleistocene faunas which would otherwise have been drowned at this time when the sea-level rose to +10 feet. At this stage the former stream valleys were completely cut off and inundated, forming the soengeis seen today. Elevation may still be in progress.

It is apparent that the Aroe Islands belong structurally to Australia, although they differ from the major units of northern Australia in view of their late upwarp. Their basement, however, appears to be similar to, say, that of Arnhem Land, and their Quaternary record provides an explanation of the features on the outer part of the Sahul Shelf. The drowned canyons of the Van Diemen Rise find an obvious analogy in the soengeis of Aroe. Above all it is clear that the outer margins of the shelf facing the East Indies has suffered pronounced movements during quite late geological times.

V. RELATIONSHIP OF AUSTRALIA TO THE EAST INDIAN ARCS.

(a) *Gravity Anomalies.*

Although no thorough gravimetric study has been made of the Sahul Shelf, Vening-Meinesz (in the Dutch submarine surveys of the East Indies) made an examination of the adjoining Timor Trough and in a few places extended it onto the shelf. This is enough to show that on the Sahul Shelf there is generally a regional isostatic anomaly of less than plus 50 milligals, which is in every way comparable to that of the Sunda Shelf.



Text Fig. 5.—Geological sketch-map of the Aroe Islands.

The Timor Trough anomalies are quite characteristic of continental margins (Vening-Meinesz, 1934). While the bathymetric curve slopes down from the shelf edge to the floor of the Timor Trough, the gravity anomaly curve maintains a high course (mostly on the positive side) for a considerable distance beyond the shelf edge before it plunges to the negative. Actually it reaches its lowest at a point roughly coinciding with the south coast of Timor (over minus 100 milligals), after which it rises steeply again to a notable positive anomaly in the interior of the Inner Banda Arc. It gives the impression that the continental structure and material of the Sahul Shelf continue out beyond the actual edge of the shelf.

In reviewing the evidence of the belt of negative anomalies coincident with the Outer Banda Arc and its "foredeep," the Timor Trough, Kuenen (1935, p. 62) says:

> "The Australian Continent influences the direction of the line of negative anomalies, but hardly in character or intensity. There is nothing in the gravity field to indicate either that the Australian block was forced up against the arcs, or that the Outer Banda Arc was originally a regular curve and was subsequently moulded up against the already existing shape of the continent."

Further discussion is to be found in his earlier contribution to Vening-Meinesz' work (1934, p. 189, *et seq.*). Many tectonic theories on the East Indies have in the past ranged from a regional "squeezing" movement to to a fully-fledged continental drift of Australia against the Lesser Sunda Arcs, but Vening-Meinesz' evidence would oppose such concepts. On the other hand, the structure of Aroe (lying as it does on the continental shelf) shows a slightly arcuate trend, paralleling the Banda Arcs, thus implying some mutual influence (Brouwer, 1920). Furthermore, observations regarding the depressed (300 fathom) continental edge, and the local rises paralleling the Timor Trough in the Sahul Bank—Cartier Reef section—suggest that such influences are not restricted merely to the Arafura Shelf, but extend all along the Sahul Shelf.

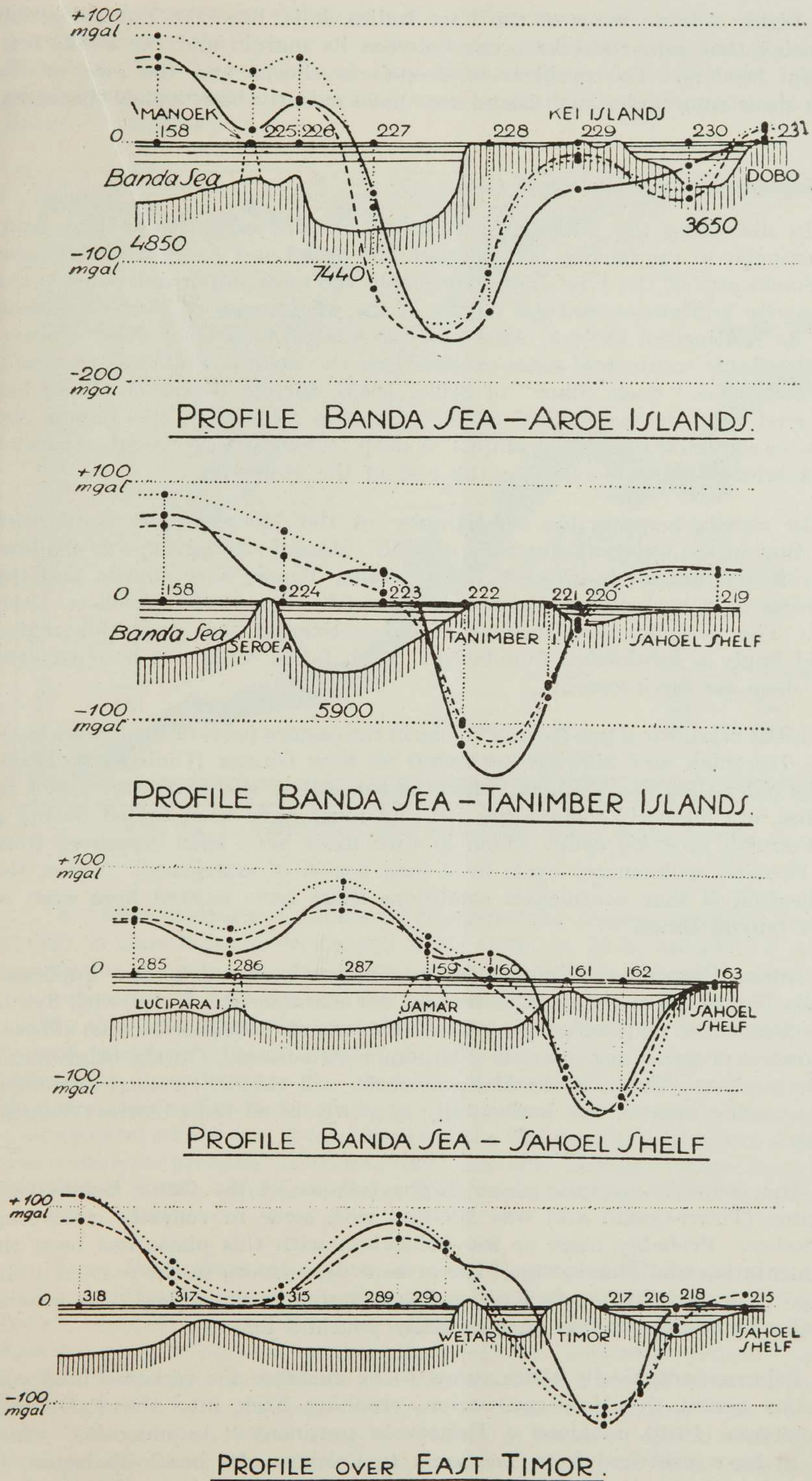
The gravity profile over the edge of the Sahul Shelf is very similar to that found in Vening-Meinesz (1941) over other continental shelves, although the other shelves are opposite ordinary ocean depressions, while the Sahul Shelf is opposite a mobile island arc in active process of deformation.

(b) *Seismicity.*

From the evidence of the coral reef studies (Teichert and Fairbridge, 1948), of the asymmetric section of the Timor Trough, and of the gravity anomalies, it would appear that the trough between Australia and the East Indies is now subsiding, or up till recently has been so.

Possibly in part because there are no recording stations, seismic data are rather sparse along this trough, as compared for example with those from the Java Trough, but a moderate number of records exist. On the 16th August, 1929, a medium-heavy earthquake was identified with an epicentre about 16½°S., 121°E. (Gutenberg and Richter, 1949). The degree of error is plotting its position is unfortunately rather large (3°), but it probably lies somewhat south-west of Scott Reef.

Futher indications occur all along the trough; it appears that a heavy shock occurred at 8°S., 132°E. (130 km. S.E. of Tanimbar), while four slight shocks occurred in the Roti-Timor-Sermata section, and numerous ones in the Aroe-Bomberai section. Since the interior of the Banda Arc is one of the



Text Fig. 6.—Gravity anomalies near the edge of the Sahul Shelf.
(From Vening-Meinesz, 1934.)

N.B.—Dotted line indicates the Hayford-Bowie anomalies; broken line the Heiskanen anomalies; solid line the Regional anomalies.

most highly seismic zones of the East Indies, it is, however, not altogether surprising that minor shocks occur between its margin and the stable continental borders. The problem of deep-focus shocks and the idea of the rising shear zone under such island arcs have recently been widely discussed.

(c) *Topographic and Geological Data.*

In discussing the intercontinental relationships of Australia and Asia, in particular in the narrow belt between the Sahul and Arafura Shelves and the Sunda arcs of the East Indies, probably the most important point is the apparently uniform continental nature of the whole mass of North Australia with its continental shelves, Aroe and the southern parts of New Guinea. A spur of this continental mass extends into the eastern Mollucca s to Misool and Soela (the " Soela Spur " of Stille, 1945), though Glaessner (1950) has suggested that the parallelism of the Vogelkop folds with the Banda Arc indicates some mutual relationships. A deep (1,000 fathom) trough separates the Australia-Misool block from the rest of the Moluccas.

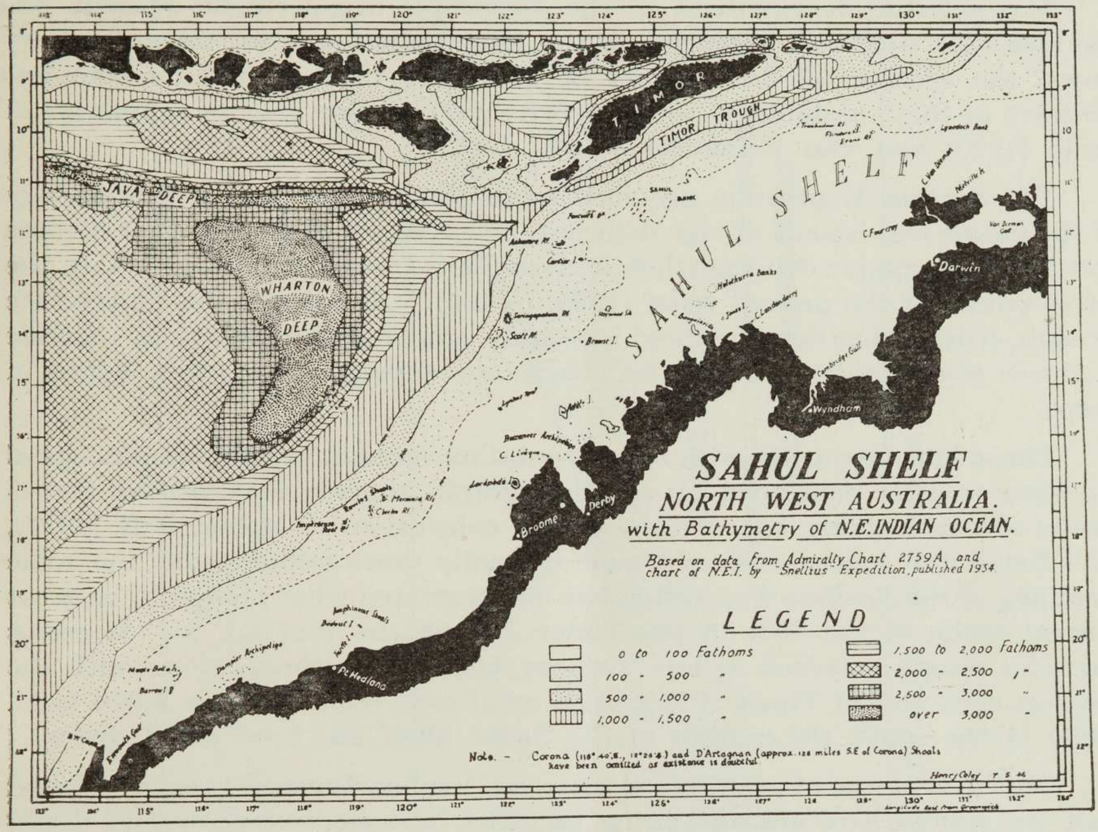
In certain respects the stratigraphy of the Moluccas has similarities with that of the adjacent Australian block. Mutual relationships in shallow-water faunas extend between N.W. Australia, Timor, New Guinea and the Moluccas right back to late Palaeozoic times (Wanner, 1931 ; Teichert, 1941, etc.). The periodic transgressions of epi-continental seas over this region would imply a continental foundation. Such facies could not be correlated with deep sea environments.

Little is known of pre-Permian rocks in the eastern parts of the archipelago. Both Devonian and Silurian are found in New Guinea (Umbgrove, 1938). Rocks older than the Permian, wherever exposed in the area from Timor to Celebes, are intensely metamorphosed and must have been folded during a pre-Permian orogenic cycle, which in turn must have been separated from the Permian sedimentary cycle by a long period of emergence. Again, the implication is that continental conditions must have existed here even in fairly remote times.

During Permian and Trias, a geosynclinal environment became impressed on the Timor-Ceram arc, as indicated by the characteristic facies, with flysch, ophiolites and so on (Umbgrove, 1938). This mobile belt later became affected by intense orogenic disturbances with nappe structures. On the other hand, in the northern Moluccas the Mesozoic rocks still exhibit foreland characteristics, resting more or less horizontally in gently tilted fault blocks (Wanner, 1931).

The principle orogenic phase in the collapse of the Outer Banda Geosyncline (Timor-Ceram arc) was Miocene with some movements continuing till today. Probably more or less coincident with this phase has been the fragmentation and foundering of the present deep basins in the eastern archipelago (Kuenen, 1935). As Kuenen has repeatedly emphasised, this present topography appears to be an essentially youthful feature.

Palaeogeographically there seems to be evidence for repeated land connections across the Moluccan region, reaching back into the Palaeozoic. Abandanon (1919) imagined a Palaeozoic continent " Aequinoctia," which was to have stretched from Tasmania to Celebes. Its break-up began, he believed, in Carboniferous times, though it is only in Permian and Trias times that we encounter geosynclinal facies. The extension of the Banda Geosyncline during the Trias to continue these conditions round northern New Guinea to New Caledonia and New Zealand (Benson, 1923, 1924, 1925) is particularly interesting. This belt would appear to be cutting the old " continent " completely in two.



Text Fig. 7.—Sahul Shelf, with bathymetry of N.E. Indian Ocean.

A " Sino-Australian Continent," postulated for Jurassic times by Neumayr (1883), is thus improbable, though Arldt (1938, p. 33–6) accepted it on zoogeographic grounds, considering it an essential route for the early monotremes (*e.g.*, ancestors of Echidna and Platypus), migrating to Australia. Umbgrove (1935) also considered the probability of a late Mesozoic land-bridge here, though perhaps only as island " stepping-stones " in places, for the floral differences alone between the Mesozoic of Cathaysia and Eastern Australia do not appear to favour a continuous connection. In the early Eocene times a continental connection at least between the Moluccas and Northern Australia was considered probable by Höfer (1908), and with further evidence is reviewed by Kuenen (1935). For later times, Mayr's results are particularly interesting (*see* Sect. IId.).

From the topographic point of view, Kuenen (1935) has demonstrated that it is difficult to draw a hard and fast line between Australia and the East Indies, especially in the New Guinea-Halmahera region. The Timor Trough does not seem to possess the characteristics of an ancient structural " seam." Earlier interpretations conceive the Banda arcs as a row of horsts, separated from Australia by a graben zone (Suess, in Sollas translation, 1908, vol. 3, p. 237 ; also Martin, 1890 ; Gregory, 1923). A new conception resulted from Molengraaff's discoveries of low-angle overthrusts in Timor (1913), and Brouwer (1920, 1925) also developed the idea of an overthrusting of the Outer Banda arcs onto the Australian block, which was to represent the traditional "foreland." The corollary of an underthrusting *vice versa* followed almost automatically. The sharpest curve of the arc through Kei and Tanimbar Islands appeared to be conditioned by a pre-existing "gulf" in the northern Australian continental block.

The extreme development of the horizontal displacement concept was the idea that Australia impinged on the East Indian arcs as late as Tertiary times, the continental drift theory of Wegener (1924), found its complete contrast in the "undatory" theories (with vertical movements primarily) of Stille (1920) and van Bemmelen (1933, 1950).

The *Snellius* Expedition provided more data on the present morphology of the basins and islands of the Moluccas, and Kuenen concluded that if there had been any major drifting, then it must date from a time well before the development of the present relief (1935, p. 105). As regards the Timor-Aroe Trough, Kuenen has demonstrated a roughly synclinal morphology in contrast to the *en bloc* subsidence or rift-like characters of most of the other Moluccan deeps.

This might favour the idea of horizontal movement, but geomorphological evidence recently confirmed by air photographs suggest that vertical movements are now going on. This was the conclusion of Molengraaff (1913), who found the south coast of Timor normally down-faulted, and the sonic sounding of the *Snellius* Expedition has demonstrated what appear to be great normal faults in the floor of the Timor Trough (*see* text fig. 8). It seems that the trough subsided in late Tertiary/Quaternary times, along with the vertical elevation of Timor (Pleistocene coral reefs stand at over 4,000 feet), while in the south the margin of the Sahul Shelf has been tilted down.

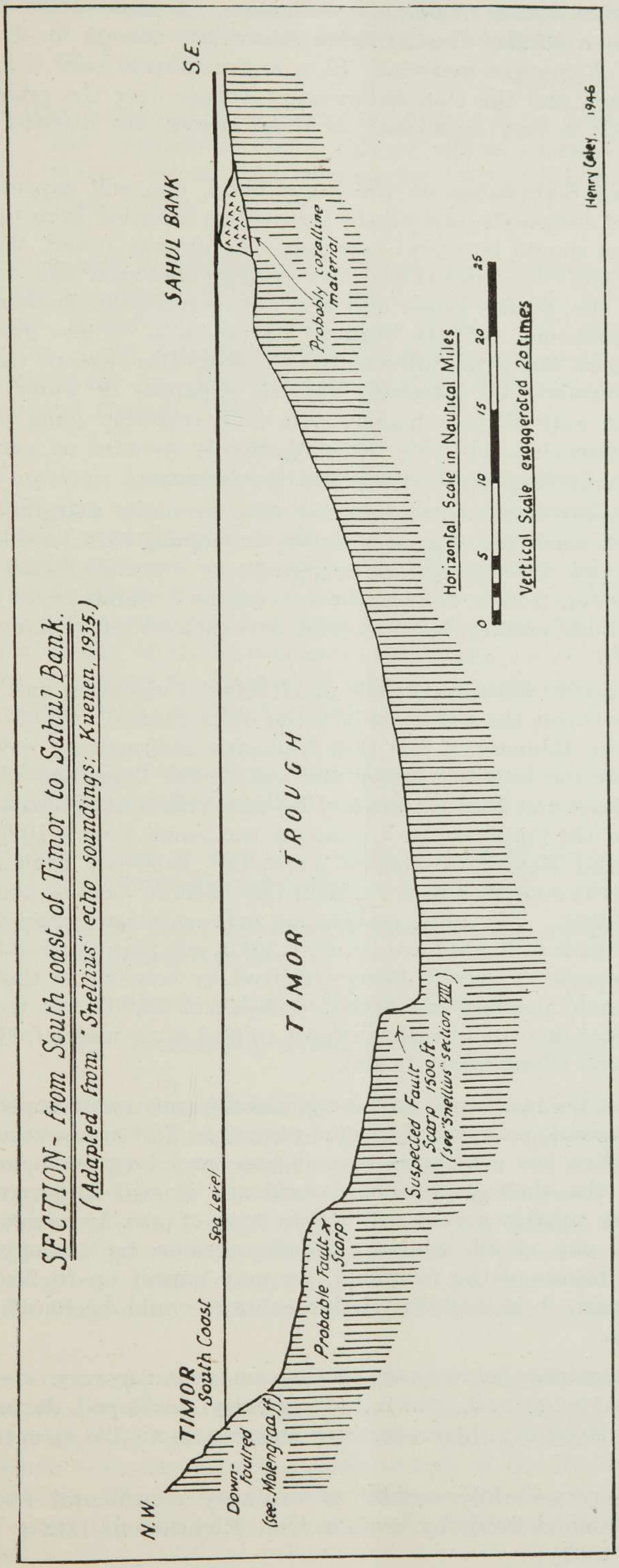
On the evidence of geophysical material, Vening-Meinesz (1934) concluded that the Banda Arcs are now being involved in a gigantic down-fold (kink) of the earth's crust, a concept which seems to accord with the structural demands (Umbgrove, 1947a). A degree of asymmetry and horizontal movement is recognised in this kinking, which corresponds to the known topographic features and to the rising shear deduced from deep-focus earthquakes.

There seems thus to be evidence for concluding that the present geomorphologic relationship of the Outer Banda Arc to the Timor-Aroe Troughs and the Sahul-Arafura Shelves is a relatively recent (*i.e.*, late Tertiary and Quaternary) phenomenon. The relationships between the Mesozoic-Tertiary mobile zone and the semi-rigid foreland appear to follow out a normal transition in the northern Moluccas, though are obscured in the Timor Trough-Sahul Shelf sector. In the Banda Arcs there is no sign of the borders of the ancient Australian continent, which may have extended much farther north and west than it does today.

VI. DISCUSSION.

In its position between Australia and Asia, facing the East Indian Archipelago, the Sahul Shelf occupies a critical zone. Matters of fundamental importance to Australian-Asiatic geotectonics and palaeogeography are bound up in this region.

The alternating rises and depressions of the Sahul Shelf seem to be situated opposite plateaus and basins on the land, and thus stand in genetic relationship to the structure of the mainland. Just as the plateaus are correlated with a more or less rigid basement of older Pre-Cambrian, sometimes



Text Fig. 8.—Section from south coast of Timor to Sahul Bank.

overlain by a thin veneer of younger sediments, the rises of the Sahul Shelf appear to have a similar Pre-Cambrian basement, though locally obscured by a thin film of younger material. Slow sedimentation only is now in progress on the shelf and the thin sedimentary veneer over the granite core in the Aroe Islands is very significant, as these islands are situated on one of the shelf rises.

In the shelf depressions on the other hand, one will expect a thicker accumulation of sediments, and all the formations recorded from the adjacent mainland basins should be found here too. As already noted, Wade (1924) and Clarke (1938) have mentioned the analogy between the "Palaeozoic Sunkland" of the Desert Basin and the two great gulfs further east, our Bonaparte Depression, and the Gulf of Carpentaria. These giant embayments are, in fact, but little different from one another, except that the two gulfs are "drowned" by relatively shallow expanses of water, while the Desert Basin is only slightly higher. All were probably gulfs periodically through the Palaeozoic, and they were repeatedly invaded at various times in the Jurassic, Cretaceous, Tertiary and Quaternary.

All the shallow shelf depressions are thus probably marginal basins of sedimentation in condition of growth today, undergoing slow local subsidence. They may, in fact, be regarded as contemporary "paralic basins" of sedimentation (Tercier, 1939), or "discordant basins" (Umbgrove, 1947a), of the types identified already in north-west Australia of late Palaeozoic origin (Teichert, 1947).

The quantitative question of how much relative elevation and depression has occurred between the blocks is of some consequence. Wade (1924) has remarked on the thinness of the post-Nullagine sedimentary cover on the rising blocks (of the order of under 500 feet). For depressed blocks, such as the Desert Basin and East Kimberley, Teichert (1947) has given a maximum of 3,000 feet for the Cambrian (not counting the basalt flows), 10,000 feet for the Devonian and 10,000 feet for the Permian. Evidence from bores near Broome and Derby suggest a post-Permian (Mesozoic to Recent) accumulation of about 2,000 feet. The total amount of sedimentation comes thus to 20 to 25,000 feet, but it may not have occurred all in one place, rather in different parts of the depression, locally being removed by erosion, so that the floor of the basin would possibly not exceed a depth of 10,000 feet today. If it were much deeper one would rather expect to find some major folding, which is notably absent (Fairbridge, 1950a).

The bulk of the movement in the mainland basins was completed by the end of the Palaeozoic and, save for some revival in Tertiary, a relatively high degree of stability has continued thus during very long geological periods. Marginally, in the shelf depressions subsidence is still in progress. Over the rises we may possibly expect only a thin layer of post-Archaean sediments, possibly hardly any at all, while in the depressions, by analogy of course with the great basins of the mainland, we may expect up to 25,000 feet of sediments. Again, it is doubtful if this column would be found all in one vertical section.

These discussions have some bearing on contemporary ideas of continental shelves in general, which have greatly developed during the last decade or so. Roughly, there are three theories as to the structure of continental shelves :

(a) They generally consist of ordinary continental rocks *in situ* planed down by erosion (von Richthofen, 1886 ; Buchanan, 1887) ;

(b) they consist of a giant lens or wedge (the " Transitional Area ") of young continental sediments, distributed out to wave-base (Murray, 1885) ;

(c) they consist of a combination of the two, a broad notch cut in the continental rock, with an apron of sedimentary debris spread out in front (Fenneman, 1902 ; Johnson, 1919 ; and Daly, 1927).

Without making a detailed analysis (see, for example, Cotton, 1918 ; Umbgrove, 1947a ; Shepard, 1948 ; Kuenen, 1950), it can be seen that each has its virtues, though the last seems most logical, and certainly seems to be true for the North Atlantic continental shelves according to geophysical evidence, both on the American side (Ewing *et al.*, 1937) and on the European side (Bullard and Gaskell, 1941).

In the northern Australian region, however, it rather looks as if all three structural varieties occur. A section run from Torres Straits to Aroe would show a shelf with crystalline basement, almost horizontal, with but the thinnest veneer of recent sediment on it (type " a "). Opposite the Desert Basin, in the Rowley Depression, probably a very thick wedge of sediments extends from far inland to several hundred miles off-shore (type " b "). The Browse Depression is clearly of the combination sort (type " c "), where the inner 50–100 miles is marked by continental islands, grading out to what appears to be a smooth-surfaced sedimentary lens beyond.

The explanation of the actual erosive sculpturing of the shelf is a further problem, which also resolves itself into three choices :

(a) Mechanical erosion by waves operating to wave-base (von Richthofen-Fenneman-Johnson school).

(b) Subaerial and shore-line erosion under conditions of shelf-emergence, due to :

(i) Glacio-eustatic lowered sea-levels, or

(ii) Tectonically flexed continental margins.

The present writer has tried to show that shore-line or inter-tidal erosion (where waves remove the mechanical debris, already dissolved and loosened by subaerial erosion) is so much more important on rocky coasts that Fenneman's and Johnson's smooth " profile of equilibrium " will never be achieved (Fairbridge, in press). Shore-line erosion during Pleistocene low eustatic oscillations provides for a limited amount of planation down to 50–60 fathoms (Umbgrove, 1929 ; Zeuner, 1945), where coarse littoral sediments of apparently Pleistocene origin are found (Fairbridge, 1946).

The low outer edge of the Sahul Shelf (300 fathoms) certainly favours the marginal flexure idea (Bourcart, 1938 ; Jessen, 1943), but it is so exceptionally low that there may be an unusual condition operating here today ; its juxtaposition with the subsiding outer trough of the East Indian mobile belt is suggestive. The evidence of large atolls and the traces of an imperfect barrier reef along this border is indicative of subsidence (Teichert and Fairbridge, 1948).

VII. CONCLUSIONS.

Summarising our conclusions, therefore, we find that :—

1. The Northern Australian continental shelves are divisible conveniently into three ; The Rowley Shelf (west of Cape Leveque), the Sahul Shelf (*sensu stricto*), and the Arafura Shelf (east of Cape van Diemen, but not including the Gulf of Carpentaria, which is contiguous to it).
2. The topography of the Sahul Shelf demonstrates evidence of subaerial exposure and erosion, including :
   (a) Plateau, terrace and cuesta type of topography.
   (b) Shallow submarine canyons crossing the shelf.
   (c) Traces of grain of older rocks in submerged ridges.
   (d) Pleistocene migratory routes shown by zoogeographic material.
3. The edge of the Sahul Shelf, at about 300 fathoms, is abnormally low, and may be explained by a slow subsidence, tilting down the continental margin opposite the East Indian arcs (an explanation favoured by the occurrences of coral atolls and interrupted barrier reef here).
4. A major " step " or break in the slope of this shelf is recognised in many places at about 55 to 60 fathoms, which may mark the break between two major cycles of subaerial erosion of the shelf, the lowest Pleistocene sea-level being generally taken as 55 fathoms.
5. Structurally the Sahul Shelf also exhibits transverse divisions into slightly higher and lower areas, termed here " rises " (10 to 40 fathoms) and " depressions " (40 to 70 fathoms).
6. The adjacent continent is found to consist of even more marked swells and basins, which exist not only topographically, but also structurally and stratigraphically.
7. The swells on the continent are major tectonic blocks of older pre-Cambrian age, peneplaned and overlain by thin deposits of subsequent periods. Their structural attitude is horizontal or undulating except near the faulted and flexed margins.
8. The basins on the continent are of considerable geological age. Downwarping occurred in them periodically from Cambrian to Recent. Thick deposits of sediments have accumulated in them (up to 25,000 feet, but probably not all in one place).
9. Depressions and rises of the shelf are arranged opposite the basins and swells of the continent. Their structural histories appear to be analogous.

   Thus we recognise from west to east :

On the continent.	*On the shelf.*
Pilbara Block	Dampier Rise
Desert or Canning Basin	Rowley Depression
Leopold Range	Leveque Rise
No equivalent	Browse Depression
North Kimberley Block	Londonderry Rise
East Kimberley Basins	Bonaparte Depression
Pine Creek-Darwin Ridge	Van Diemen Rise
N.E. Arnhem Land—Wessel I. Ridge	Wessel Rise

Beyond the Van Diemen Rise we are already on the Arafura Shelf, with an Arafura Depression (Fairbridge, 1951) corresponding to the Torres Straits depression between New Guinea and Cape York Peninsula ; the Merauke Rise, corresponding to the Oriomo uplift of southern New Guinea ; and, finally, the Snow Mountains Trough, in direct continuation of the Papuan Trough farther east. East of the Arnhem Land block lies the Carpentaria Depression.

10. Continental rocks on the Sahul Shelf are unknown except quite close to land. On the Arafura Shelf, however, the Aroe Islands provide a valuable "window," serving to show the underlying rocks : apart from Tertiary shallow-water marine sediments, there is a small occurrence of granite, indicating the continental basement at shallow depth, as also in southern New Guinea.

11. The only other islands on the shelf are coral islands. These springing from shallow water may have grown up from the bottom ; those from moderate depths may be traced to the fringing reefs of Pleistocene low eustatic sea levels. But those rising from 100 to 300 fathoms require some element of subsidence to explain them. These deep-seated reefs (mainly atolls) rise from the areas already regarded as subsiding depressions on other grounds.

12. Contemporary sedimentation on the shelf areas is not well known, but wherever sampled suggests either local sedimentation due to coral reef erosion, or elsewhere show terrigenous sedimentation with glauconite muds and residual sands. Here sedimentation may even be suspended for long periods and more resistant minerals are concentrated by reworking. A thin veneer of younger sediments is thus to be expected over the rises, and even in the depressions, where representatives of most geological periods may be predicted, many are likely to be in reduced sequences because of the regional history of low relief and slow sedimentation.

13. Stratigraphic and palaeogeographic data indicate that much of Northern Australia and its continental shelf region have been continental since Archaean times ; all subsequent .sediments are neritic in character with no trace of deep-sea or ortho-geosynclinal facies. Sedimentary basins in the area cannot therefore be considered as as ortho- or para-geosynclines, and are perhaps best described as *paralic basins* (Tercier).

14. Palaeogeographic and faunistic connections suggest that this continental area (either as land or shelf) formerly extended far to the north-west, including the northern Moluccas in Mesozoic times and possibly even to reaching to the Celebes in the late Palaeozoic. The geosynclinal evolution of the Timor-Banda Arc set in with the Permian and Trias, apparently encroaching on the old continent.

15. The unmodified (original) Wegenerian idea of an Australian continent, drifting several thousand kilometers to impinge upon the Moluccan region in late Mesozoic to Tertiary times, cannot therefore be entertained.

16. From Timor south-westwards, however, there is nothing to suggest that the present limit of the continental shelf (and slope) has not approximated to the margin of the continent for very long periods.

17. Palaeozoic land connections between Australia and the rest of Gondwanaland could not have been towards the north-west, because repeated marine invasions seem to have come from this direction. In Permian times continuous marine connections reach down from the Moluccas as far as 30°S. latitude, so that any land connection with the rest of the Gondwana units would have to be via the extreme northern or southern parts of the continent, not the west. Alternatively, the biogeographical data might perhaps be explained by island links.

BIBLIOGRAPHY.

ABENDANON, E. C., 1919. Aequinoctia, an old Palaeozoic continent. *Journ. of Geol.*, vol. 27, pp. 562–578.

ADMIRALTY, 1934. Australia Pilot, vol. V, *Hydrographic Department*, London (3rd. ed. by Capt. L. D. Penfold).

ANON, 1928. Limits of Oceans and Seas, *Internat. Hydr. Bur.* (Monaco), Sp. Publ. No. 23, 24 pp., with map.

ARLDT, T., 1938. Die Entwicklung der Kontinente und ihrer Lebewelt. Berlin (Borntraeger), 2nd ed.

van BAREN, F. A., and KIEL, H., 1950. Contribution to the sedimentary petrology of the Sunda Shelf. *Journ. Sed. Pet.*, vol. 20, pp. 185–213.

BASEDOW, H., 1916. Physical Geography and Geology of the Western Rivers District. *Proc. Roy. Geogr. Soc. Aust.* (S.A.), vol. 16 (1914–15), pp. 143–217.

BASEDOW, H., 1917. Narrative of an expedition of exploration in North-Western Australia. *Proc. Roy. Geogr. Soc. Aust.* (S.A.), vol a8, pp. 105–295 (see especially " A synopsis of the geology........," pp. 240–249).

van BEMMELEN, R. W., 1933. Die neogene Struktur des Malayischen Archipels nach der Undationstheorie. *Proc. Kon. Ak. v. Wet., Amsterdam.* vol. 36, pp. 888–897.

van BEMMELEN, R. W., 1949. The Geology of Indonesia. The Hague (Govt. Printing Office), 2 vols.

BENSON, W. N., 1923. Palaeozoic and Mesozoic seas in Australia. *Trans. New Zeal. Inst.*, vol. 54 (for 1922), pp. 1–62.

BENSON, W. N., 1924. The structural features of the margin of Australasia. *Trans. New Zeal. Inst.*, vol. 55 (for 1923), pp. 99–137.

BENSON, W. N., 1925. Stratigraphy and structure of the northern and eastern margin of Australia. *Verb. Geol-Mijnb. Gen. voor Ned. en Kol.* Geol. ser. vol. 8 (Verbeek Gedenkboek), pp. 53–72.

BOURCART, J., 1938. La marge continentale. Essai sur les régressions et transgressions marines. *Bull. Soc. Geol. Fr.*, 5 ser., vol. 8, pp. 393–474.

BROUWER, H. A., 1917. Geologisch overzicht van het oostelijk gedeelte van den Oost-Indischen Archipel : Stratigrafie, Tektoniek, Vulkanisme. *Jb. v. h. Mijnwezen in Ned-Indie*, vol. 46, pt. 2., pp. 145–452.

BROUWER, H. A., 1920. On the crustal movements in the region of the curving rows of islands in the eastern part of the East Indian Archipelago. *Proc. Kon. Akad. Wet., Amsterdam*, vol. 22, pp. 772–782.

BROUWER, H. A., 1925. The Geology of the Netherlands East Indies. New York (Macmillan), 160 pp.

BROWN, H. Y. L., 1895. Government geologists report on explorations in the Northern Territory. *South. Aust. Parl. Pap.* (Adelaide), no. 82 (incl. R. Etheridge : Contr. to Palaeontology No. 8).

BROWN, H. Y. L., 1906. Explorations made by the Government Geologist, 1905. *South Aust. Parl. Pap.* (Adelaide) No. 55 (incl. R. Etheridge) : Contrib. to Palaeontology, no. 15 and 16).

BROWN, H. Y. L., 1908. Geological reconnaissance from Van Dieman Gulf to the McArthur River, etc. *South Aust. Parl. Pap.* (Adelaide) No. 25, 12 pp.

BRUNNSCHWEILER, R., 1951. Notes on the geology of Dampier Land, North-Western Australia. *Aust. Journ. Sci.*, vol. 14, pp. 6–8.

BUCHANAN, J. Y., 1887. On the landslopes separating continents and ocean basins, especially those on the west coast of Africa. *Scot. Geogr. Mag.*, vol. 3.

BULLARD, E. C. & GASKELL, T. H., 1941. Submarine seismic investigations. *Proc. Roy. Soc., London.* ser. A. vol. 177, pp. 476–499.

CADELL, H. M., 1899. Some Geological Features of the coast of Western Australia. *Trans. Edinburgh Geol. Soc.*, vol. 7 (1895–6), pp. 174–182.

CAREY, S. W., 1938. The morphology of New Guinea. *The Australian Geographer*, vol. 3, pp. 3–31.

CLARKE, E. de C., 1938. Middle and West Australia. *Regionale Geologie der Erde* (Leipzig) vol. I, pt. vii, 58 pp.

COTTON, C. A., 1918. Conditions of deposition on the continental shelf and slope. *Journ. of Geol.*, vol. 26, pp. 135–160.

DALY, R. A., 1927. The geology of St. Helena Island. *Proc. Amer. Acad. Arts. Sci.*, vol. 62, pp. 31–92.

DALY, R. A., 1934. The changing world of the Ice Age, New Haven, 271 pp.

DAMPIER, W., 1703. Collection of Voyages, London, 3 vols.

DAVID, T. W. E., 1932. Explanatory notes to accompany a new Geological Map of the Commonwealth of Australia. *C.S.I.R.* (Sydney), 177 pp. (with map).

DICKERSON, R. E., 1941. Molengraaff River : a drowned Pleistocene stream and other Asian evidences bearing upon the lowering of sea level during the Ice Age. *Univ. Pennsylvania* (*Bicentennial Conf.*), Philadelphia, pp. 13–30.

EARL, G. W., 1845. On the Physical structure and arrangement of the islands of the Indian Archipelago. *Journ. Roy. Geogr. Soc.* (London), vol. 15, pp. 358–365.
(N.B.—In original, author is given as EARLE, W., apparently an error for George Windsor EARL, then Commissioner for Crown Lands at Port Essington, N.T., and author of other works on the area.)

EDWARDS, A. B., 1942. Some basalts from the North Kimberley, Western Australia. *Journ. Roy. Soc. West. Aust.*, vol. 27 (1940–41), pp. 79–93.

EDWARDS, A. B., & CLARKE, E. de C., 1940. Some Cambrian basalts from the East Kimberley, Western Australia. *Journ. Roy. Soc. West. Aust.*, vol. 26 (1939–40), pp. 77–94.

EWING, M., CRARY, A. P., & RUTHERFORD, H. M., 1937. Geophysical investigations in the emerged and submerged Atlantic coastal plain. *Bull. Geol. Soc. Am.* vol. 48, pp. 753–802.

FAIRBRIDGE, R. W., 1946. Coarse sediments on the edge of the continental shelf. *Amer. Journ. Sci.*, vol. 245, pp. 146–153.

FAIRBRIDGE, R. W., 1948. Discoveries in the Timor Sea, North-West Australia. *Journ. Proc. Roy. Aust. Hist. Soc.* (Sydney), vol 34, pp. 193–218.

FAIRBRIDGE, R. W., 1950a. Problems of Australian geotectonics. *Scope* (*Journ. Sci. Un., Univ. W.A.*), vol. 1, No. 5, pp. 22–28.

FAIRBRIDGE, R. W., 1950b. Recent and Pleistocene coral reefs of Australia. *Journ. of Geol.*, vol. 58, No. 4, pp. 330–401.

FAIRBRIDGE, R. W., 1951. The Aroe Islands and the continental shelf north of Australia. Scope (*Journ. Sci. Union, Univ. W. Aust.*), vol. 1, No. 6, pp. 24–28.

FAIRBRIDGE, R. W., in press. Marine Erosion. *Seventh Pac. Sci. Congr.* (N.Z.).

FENNEMAN, N. M., 1902. Development of the profile of equilibrium of the subaqueous shore terrace. *Journ. Geol.*, vol. 10, pp. 1–32.

GALLIHER, E. W., 1936. Glauconite genesis. *Bull Geol. Soc. Am.*, vol. 46, pp. 1351–1366.

GENTILLI, J., 1949. Foundations of Australian bird geography. *Emu*, vol. 49, pp. 85–129.

GLAESSNER, M. F., 1950. Geotectonic position of New Guinea. *Bull. Amer. Assoc. Petr. Geol.*, vol. 34, pp. 856–881.

GREGORY, J. W., 1913. The nature and origin of fiords. London (John Murray), 542 pp.

GREGORY, J. W., 1923. The Banda arc: its structure and geographical relations. *Georgr. Journ.* vol. 62, pp. 20–32.

GREGORY, J. W., and others, 1924. The Geology of the Aru Islands. *Geol. Mag.*, vol. 61, pp. 52–72.

GUPPY, D. J., and ÖPIK, A. A., 1950. Discovery of Ordovician rocks, Kimberley Division, W.A., *Aust. Journ. Sci.*, vol. 12, pp. 205–206.

GUTENBERG, B., and RICHTER, C. F., 1949. Seismicity of the Earth. Princeton (Univ. Press), 273 pp.

HELDRING, O. G., 1910. De Zuidkust van Nieuw-Guinea. *Jaarboek v.h. Mijnw. Ned. O. Indie*, vol. 38 (for 1909), pp. 83–203.

HENDRIKS, S. B., and ROSS, C. S., 1941. Chemical composition and genesis of glauconite and celadonite. *Amer. Mineralogist*, vol. 26, no. 12, pp. 683–708.

HILLS, E. S., 1946. Some aspects of the tectonics of Australia. *Journ. Proc. Roy. Soc. N.S.W.*, vol. 79, pp. 67–91.

van HOEVELL, G. W. W. C., 1889. De Aroe-eilanden. *Tijdschr. voor Ind. T.L. en Volk*, vol. 33, pp. 57–101.

HÖFER, H., 1908. Das polynesische alteozäne Festland. *Sitzb. kon. Akad. Wis. Wien*, vol. 117, pt. 1, pp. 513–518.

HORSBURGH, J., 1811. Directions for sailing to and from the East Indies, China, New Holland, Cape of Good Hope, etc. London, 2 vols.

JENSEN, H. I., 1914. Geological report on the Darwin mining district; McArthur River district; and the Barkly Tableland. *Bull. of N.T. Dept. of Ext. Affairs*, Melbourne, no. 10, 38 pp.

JENSEN, H. I., 1923. Some geological features of Northern Australia. *Proc. Roy. Soc. Qld.*, vol. 34, pp. 105–122.

JENSEN, H. I. and PLAYFORD, E. C., 1913. Geology of the Northern Territory of Australia. *Dept. Ext. Affairs* (*Australia*).

JESSEN, O., 1943. Die Randschwellen der Kontinente. *Petermanns Mitt.*, Ergänzungshaft 241.

JOHNSON, D. W., 1919. Shore Processes and Shoreline Development. New York. (Wiley), revised ed., 1938.

JUTSON, J. T., 1934. The physiography (Geomorphology) of Western Australia. *Geol. Surv. West. Aust.*, Bull no. 95 (2nd. rev. ed.).

KEBLE, R. A., 1947. Notes on Australian Quaternary climates and migration. *Mem. Nat. Mus. Vic.*, No. 15, pp. 28–81.

KING, P. P., 1827. Narrative of a survey of the intertropical and western coasts of Australia, performed between the years 1818 and 1822. London (Murray), 2 vols.

KÖLBEL, H., 1945. Die Tektonische Entwicklung Australiens. *Geotektonische Forschungen*, No. 7/8, pp. 154–209.

KOSSINNA, E., 1921. Die Tiefen des Weltmeeres. *Veröff. Inst. f. Meereskunde*, Berlin, N.F., A. Geogr.-naturw. Reihe, no. 9, 70 pp.

KRÜMEL, O., 1897. Handbuch der Ozeanographie, Stuttgart, 2 vols. (2nd ed., 1907).

KUENEN, P. H., 1933. Geology of Coral Reefs. *The Snellius Expedition*, vol. 5 Geological Results, pt. 2, 125 pp.

KEUNEN, P. H., 1935. Geological Interpretation of the bathymetrical results. *The Snellius Expedition*, vol. 5, Geological Results, pt. 1, 124 pp.

KUENEN, P. H., 1939. Sediments of the East Indian Archipelago. In Trask: *Recent Marine Sediments* (A.A.P.G.), pp. 348–355.

KUENEN, P. H., 1950. Marine Geology. New York (Wiley), 568 pp.

KUENEN, P. H. and NEEB, G. A., 1943. Bottom Samples. *The Snellius Expedition*, vol. 5, Geological results, pt. 3, 268 pp.